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DENSE FRICTION COURSE EVALUATION 1978 TO 1983 CONTRACTS

MATERIALS INFORMATION

ENGINEERING MATERIALS OFFICE

DENSE FRICTION COURSE EVALUATION

1978 to 1983 Contracts

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EXECUTIVE SUMMARY

In 1978, Dense Friction Course (DFC) was approved by the Pavement Advisory Committee and Provincial Road Program Planning Committee for use on main highways with excess of 5000 AADT/lane. The approval was based on the superior three year frictional performance of DFC mixes over traditional HL-1 mixes on the Highway 401 (Toronto By-Pass) test sections from Dufferin Street to Highway 400 placed under Contract 74-20. Subsequently the Task Force on Performance of Bituminous Friction Courses was established to monitor (test and inspect) the performance of bituminous friction course surfaces.

The original DFC mixes provided for 45% retained on the 4.75 mm sieve. The Task Force recommended that the percentage retained on the 4.75 mm sieve for DFC mixes should be increased from 45% to 55% to ensure long lasting macro-texture and friction values, this would also reduce asphalt cement demand. In 1982, the Engineering Materials Office initiated this change in coarse aggregate content.

Shortly after the change in coarse aggregate there were severe icing problems identified with DFC installations particularly abutting impermeable lower cost paved shoulders. It was felt that DFC permeability was the problem. Central Region reverted back to 45% DFC for any projects where DFC abutted paved shoulder or concrete gutter because 45% DFC was perceived as being less permeable.

This investigation has shown there has been no comparative field installations that scientifically assess the differences between 45% DFC and 55% DFC. Visual reviews by both the Task Force and members of the Bituminous Section indicate 55% DFC provides superior macro-texture, a key component for high speed friction resistance. In general there has been a lack in follow up test data on full scale DFC installations regarding the review of construction test results and the review of parameters such as friction, permeability and maintenance procedures.

In the compilation of this study, design information and construction test results for contracts from 1978 to 1983 were reviewed. The following major points were noted:

(i) use of steel slag predominated.

(ii) DFC mixes exhibit high to very high stability.

(iii) the 45% DFC mixes tend to be built with slightly higher coarse aggregate content and 55% DFC mixes tend to be built with slightly lower coarse aggregate contents than designed.

(iv) DFC mixes are generally constructed with higher void contents than designed indicating some reluctance on Quality Assurance staff to make field adjustments to mix designs.

To obtain information on maintenance procedures on DFC a telephone survey of all patrols was undertaken. This survey indicated that most Dense Friction Course pavements are "dense" in name only and three quarters of the projects provide for varying degrees of permeability. Low permeability DFC pavements can have the same maintenance procedures (i.e. windrowing of salt/sand) as other H.L. pavements. At higher permeabilities, DFC pavements require different maintenance procedures (higher salt/sand ratios, broadcasting of material). In several instances maintenance staff had problems the first winter because they were not warned of the presence of DFC or that it would require different maintenance procedures from the previous pavement.

Based on a pavement investigation on Highway 401 from Oshawa to Highway 115 Port Hope District (where severe DFC icing conditions occurred during the 1982/83 winter) permeability increases as coarse aggregate content increases. Mixes with higher coarse aggregate contents tend to be harder to compact which provides for higher in-place pavement voids. The HL4 paved shoulders are virtually impermeable which provides for water being trapped in the permeable DFC driving lanes and contributed to the severe icing problems. Through increased maintenance efforts and some remedial work the

problems have not reoccurred but the maintenance staff feel they are "living on the edge" of having a repeat of the problems. All DFC pavements, which ranged from 41% to 56% in coarse aggregate contents, in the stretch of Highway 401 east of Oshawa exhibited high permeability and had icing problems.

This report concludes that 55% DFC must be designed similar to an Open Friction Course and placed full width to provide for lateral drainage, whereas the traditional design had been 45% DFC on main lanes with HL3 or HL4 paved shoulders. The traditional design is about 13% less expensive than full width DFC, however as previously mentioned many of the 45% DFC mixes are exhibiting permeability. The foregoing recommendation is the current practice.

While it would be possible to consistently build impermeable DFC pavements which would reduce icing problems, it is not practical. To increase impermeability, DFC pavements would require:

(i) higher awareness and willingness among Quality Assurance staff to make adjustments to field mix designs

(ii) tighter acceptance limits on coarse aggregate content (and possibly asphalt cement content) to ensure a close conformance with design values

(iii) closer monitoring and improved compactive effort by the Contractor

(iv) tight restrictions on aggregate characteristics such as gradation, absorption, and bulk relative density. This may result in the prohibition of the use of steel slag for DFC pavements.

(v) other construction restraints such as no fall paving and the possible non-use of drum mixers for DFC

Failure to provide for any of the above may result in a permeable DFC pavement. Recognizing the prohibitive nature of the restrictions, the Bituminous Section recommends that:

1) The Ministry acknowledge the permeable nature of DFC mixes and place DFC full width.

2) That test sections be installed to evaluate the performance of 45% DFC versus 55% DFC. In the interim the Ministry should continue with the use of 55% DFC.

Other recommendations include:

- Maintenance Office should review and establish appropriate winter maintenance procedures for DFC.

- Use of 45% DFC on bridge decks with special low void criteria to minimize permeability should be permitted.

- DFC placement should be sequential to avoid DFC installations in isolation particularly at end of patrols.

- Bituminous Section should continue the development of new techniques for providing impermeable DFC pavements.

- Maintenance staff should be informed of the placement of DFC.

Many of the recommendations regarding maintenance procedures have been implemented since the drafting of this report.

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1. INTRODUCTION

In 1974, a series of bituminous test sections were installed on the Highway 401, Toronto By-Pass in the westbound core lanes from Dufferin Street to Highway 400. These test sections consisted of open graded and dense graded mixes using a variety of aggregates. The most striking discovery of the project was the excellent frictional characteristics of mixes containing crushed traprock and steel slag fine aggregate and the low friction numbers of many of the mixes containing natural sand blended with limestone screenings. Based on the three year performance of these sections, recommendations were made to the Pavement Advisory Committee and the Provincial Road Program Planning Committee which resulted in Ministry approval of the use of Open Friction Course (OFC) mixes on urban freeways and Dense Friction Course (DFC) mixes for main highways carrying in excess of 5000 AADT/lane.

Dense Friction Course mixes are dense graded mixes providing high frictional resistance. The coarse and fine aggregates are premium quality crushed materials such as traprock, steel slag, or blast furnace slag. Originally, DFC mixes contained 45% by mass retained on the 4.75 mm sieve. The commitment of the Ministry to construct more friction course pavements made it essential to evaluate the field performance of these mixes and make any necessary changes. To provide this evaluation, a Task Force on the Performance of Bituminous Friction Courses was established. One of the recommendations of the Task Force was to increase the percent retained 4.75 mm sieve to 55% by mass. In 1982 the Bituminous Section, Engineering Materials Office (EMO) initiated a change in the percent retained 4.75 mm sieve to 55%.

The Task Force identified that some of the early DFC projects had maintenance complaints of icing the first winter. Shortly after the change in coarse aggregate contents there was renewed maintenance complaints with several DFC installations. These problems included severe icing on Highway 401 between Oshawa and Highway 35/115 in the 1982/83 winter and flooding on Highway 2 at Whites Road in Pickering. At the time the problems were attributed to the permeability of the DFC. Most projects in Central Region

(either at construction or design stage) were changed back to 45% retained on the 4.75 mm sieve (excluding projects with full width DFC) (See Appendix A). The DFC mix with 45% coarse aggregate was perceived as having fewer permeability problems.

The purpose of this report is to resolve the issue of percentage retained 4.75 mm sieve in DFC by documenting the following:

- the history of development of DFC in Ontario (i.e. change in coarse aggregate content)
- performance history of both 45/55 and 55/45 mixes
- current maintenance procedures and problems on both mix types
- recommendations for future action

2. HISTORICAL BACKGROUND

The sequence of development of DFC mixes was:

1) 1969, placed as HL-1 Modified mixes on Highway 400 in conjunction with 'Studies of Studded-Tire Damage'

2) 1974, Highway 401 Test Sections, Toronto By-Pass

3) 1978, Lindsay Test Sections

4) 1979, Task Force on Performance of Bituminous Friction Courses

(5) 1982, Bituminous Section initiates change in percent retained 4.75 mm sieve

2.1 Highway 400 Test Sections

In the fall of 1969, a series of 27 test sections was installed on Highway 400 northbound (north of King Side Road). The primary purpose was to document the effect of studded-tires on hot mix pavements and develop wear resistant mixes (1). Three of the sections installed had mix compositions of 40%, 50% and 60% traprock coarse aggregate respectively, all with traprock screenings as the fine aggregate. The performance on all three sections was poor (i.e. large loss of fine aggregate and coarse aggregate) with very poor performance on the section with 60% coarse aggregate. The mixes were very permeable and difficult to compact. The average wear on the three sections associated with studded-tires was rather poor (more wear due to loss of stone than standard HL 3, normal HL 1, etc.). High friction numbers were attained on these three sections and they remained high into the following year. Unfortunately these sections were overlaid after two years of service when Highway 400 was widened. However, the experience gained with these sections was used to provide insight into mix combinations for the Highway 401 test sections.

2.2 Highway 401 Test Sections

In the summer of 1974, eighteen bituminous overlay test sections were placed on Highway 401 Toronto By-Pass between Dufferin Street and Highway 400 under Contract 74-20. The purpose of test sections was to assess the durability and friction characteristics of various types of mixes and mix compositions, and to determine how many lifts of pavement were required to rehabilitate the Highway 401 concrete pavement. The mix compositions and designs are detailed in Appendix B.

There were four test sections that would now be considered DFC mixes. They were:

Section 3) with 45% traprock coarse aggregate and 55% traprock screenings

Section 7) with 45% steel slag coarse aggregate and 55% steel slag screenings

Section 9) with 45% blast furnace slag coarse aggregate and 55% blast furnace slag screenings

Section 6) with 60% traprock coarse aggregate, 38% traprock screenings and 2% asbestos fibers. (This section will be excluded from the evaluation because of the indeterminant effect of the asbestos fibers)

Mix proportions for all the test sections were selected on the basis of Ministry experience with the friction characteristics of freeway surface course layers, a review of mixes used by other agencies and the earlier Highway 400 test sections used to determine the practicality of using several special mixes (2).

Studies conducted by Ryell et al four years after installation of the test sections lead to the following conclusions (2):

1) All bituminous mixes tested provided substantially higher friction numbers than the previous concrete pavement (See Appendix B).

2) All mixes demonstrated a decline in friction values during the first four years of service. Therefore initial target friction numbers must be substantially greater than the required minimum. For the purpose of comparison, Ryell et al assigned a friction number of 31 measured at 100 km/h to be the minimum target value for this section of Highway 401.

3) The early decline in friction values was primarily due to reduced macro-texture depth as the coarse aggregate particles were pressed into the pavement from wheel loads.

4) The mixes with a natural sand fine aggregate blend gave the lowest friction numbers after four years of service.

5) The open graded traprock mixes and DFC mixes achieved friction numbers close to or above the minimum specified in the driving lane. In the DFC mixes the characteristics of the fine aggregate component affect the macro-texture depth attained. The mixes with steel slag, blast furnace slag or traprock screenings as the fine aggregate had better macro-texture than the mixes with natural sand.

6) For dense graded mixes the blast furnace slag and the steel slag appeared to have better frictional properties than the traprock aggregates.

Based on the three year performance of these test sections, in 1978 the Ministry began using OFC on urban freeways and DFC for main highways carrying in excess of 5000 AADT/lane.

2.3 Lindsay Test Sections

In 1978, 17 bituminous test sections were placed on Highway 7 near the town of Lindsay. The purpose of these test sections was to develop surface mixes which provided and maintained adequate surface texture and friction values under moderate traffic. Both open graded mixes and dense graded mixes (with 55% retained 4.75 mm sieve) with various aggregate combinations (limestone, Maple Ridge crushed igneous gravel, natural sand) were installed. None of the sections can be considered "DFC" or "OFC" pavements (i.e. meeting the requirements of Ontario Provincial Standard Specifications (OPSS) Special Provisions 321 and 311 respectively).

Based on the Lindsay test sections the following conclusions were drawn (3):

1) The use of high percentage of crushed coarse aggregate (i.e. 55% and 65%) in bituminous mixes appear to produce better and longer lasting surface textures and higher friction levels. Such mixes require less asphalt cement.

2) For moderate traffic volumes the frictional levels depend primarily on the quality (i.e. angularity and harshness) of the coarse aggregate. In a subsequent paper (4) it was related that regardless of the fine aggregate type, the same coarse aggregate would provide similar frictional levels.

2.4 Task Force on Performance of Bituminous Friction Courses

The original task force was formed in 1978. The purpose of the Task Force was to monitor (test and inspect) the performance of bituminous friction course surfaces, recommend changes to specifications where necessary and identify areas where additional research was required. The Task Force (Messrs. Corkill, Kamel, McDougall) issued the first progress report in August 1979. Pertaining to DFC, the progress report (5) noted the following:

- DFC mixes yielded friction numbers above 30 at 100 km/h which the Task Force considered satisfactory for high speed freeway conditions.

- late fall paving should be avoided and pavement thickness should not be less than 30 mm.

A new Task Force was subsequently formed in November of 1980. The Task Force consisting of Messrs. Lynch, Prakash, Rogers, Gunter and Ksenych decided 'there was no pressing need for the Task Force to continue'. To summarize the Task Force efforts a report was prepared by Messrs. J. McDougall and P. Ksenych. This report highlighted the following items: (6)

- winter performance problems (icing complaints) were attributable to windrowing salt application rather than broadcasting and the permeable nature of the DFC (i.e. brine solution penetrates rather than spreads full width). The authors felt it should be general knowledge that DFC mixes (and OFC mixes) require the broadcasting (spinning) of deicing salt and a slightly higher application rate for winter snow and ice control.

- reduction in accidents after reconstruction may be a function of improved surface texture but also would reflect revisions in alignment, additional lanes, longer lane change tapers, etc.

- fresh DFC pavements appear to require the same frequency of zone painting as standard surface course mixes.

- DFC mixes appear to the observant driver to be quieter than the normal HL 1 and HL 3 surface courses.

The recommendations of the 1980 Task Force were:

- DFC mixes should be placed in lifts not less than 30 mm.

- the percentage retained on the 4.75 mm sieve for DFC mixes should be increased from 45% to 55% to ensure long lasting macro-texture and friction values, this would also reduce asphalt cement demand.

- 'late fall' paving should be avoided.

- DFC resurfacing should be placed in combination with a levelling course to reduce the chance of thin lifts and subsequent ravelling.

- OFC shoulder mix should consist of cheaper local aggregates (the concept could be expanded to permeable DFC pavements).

- tandem (echelon) paving should be used wherever practical to reduce joint ravelling.

- promptly rout and seal pavement cracks in DFC pavements.

- it is necessary to inform the maintenance patrols of the need to broadcast deicing salts on OFC and DFC surface course mixes.

- dissolve the Task Force and assign Engineering Materials Office the responsibility to continue monitoring and evaluation of OFC and DFC mixes.

The original recommendation for the change in coarse aggregate contents from 45% to 55% for DFC pavements came from Mr. N. Kamel, formerly with the Research and Development Branch, MTC (7) (Appendix C). This was subsequently included in the Task Force on Performance of Bituminous Friction Course Pavements. Mr. Kamel's recommendation was based on the following points:

1) The improved friction values of the HL1 mix with 55% retained 4.75 mm sieve (Test Section 4) over the HL1 mix with 45% retained 4.75 mm sieve (Test Section 1) of the Highway 401 test sections (Contract 74-20) (Appendix C)

2) Similar observations were observed on two steel slag mixes with 45% and 55% retained 4.75 mm sieve. (Appendix C).

3) Studies elsewhere had indicated that optimum coarse aggregate for deformation resistance to be 55% for crushed aggregates. In addition Japan had been employing high coarse aggregate contents in asphalt mixes (55% to 60%) primarily for excellent frictional characteristics and high resistance to rutting.

4) Asphalt mixes with 55% retained 4.75 mm sieve generally require 0.5% to 0.6% less asphalt cement than traditional mixes with 45% retained 4.75 mm sieve.

The Task Force examined much of Kamel's deductive work and field application of the various mixes. With poor performance of some DFC mixes with 45% retained 4.75 mm sieve (i.e. Highway 7 at Georgetown) and an empirical knowledge of mix design performance particularly with HL 1 type mixes, it was felt that the percentage retained 4.75 mm sieve should be increased from 45% to 55%.

2.5 Change in Percentage Retained 4.75 mm Sieve

In keeping with the recommendations of the Task Force the decision was made by the Engineering Materials Office in 1982 to change the percentage retained on the 4.75 mm sieve from 45% to 55% for DFC mixes. The factors that weighed heavily in the decision are described in the previous section.

In addition, the visual review by several members of the Task Force had indicated there were installations with 45% retained on the 4.75 mm sieve where the macro-texture had exhibited immersion under traffic, notably Highway 7 at Georgetown.

Shortly after the change to 55% retained 4.75 mm sieve in DFC mixes, it was recognized that for certain mixes, designs by weight or mass were not equivalent to mix designs by volume. For materials such as steel slag or blast furnace slag or when different materials are used for coarse and fine aggregate the relative density of the coarse aggregate may be higher than the relative density of the fine aggregate. For example to obtain 55% retained on the 4.75 mm sieve by volume in steel slag mixes they require about 57% retained 4.75 mm sieve by mass. For blast furnace slag the discrepancy between mixes by volume and mixes by mass is even greater. To ensure the coarse aggregate content was maximized, mix proportions were specified by volume. Actual mix designs provided to the field are still specified by mass but reflect a 'desired' coarse aggregate content by volume.

3. REVIEW OF CONTRACT DATA (1978 TO 1983)

The inital phase of this evaluation was to identify all locations in Ontario where DFC had been placed. Contract files were then reviewed to identify the following:

1) types of aggregates used

2) mix design values

3) mean and standard deviation of laboratory plant check values

4) mean and standard deviation of field test values (acceptance testing) and

5) tender quantities

The accumulated data is given in Appendix D.

3.1 Design Information

Aggregate Types

The period of evaluation covered 1978 to 1983 contracts. During this period there were 88 job mixes on some 79 contracts where DFC was the surface course pavement. Of these 88 job mixes, 53 contained steel slag aggregates, 32 contained traprock aggregates, one contained dolomitic sandstone and the remaining two contained blast furnace slag coarse aggregate combined with steel slag fine aggregate. One contract had traprock coarse aggregate with steel slag fine aggregate, while the remaining contract had steel slag coarse aggregate and traprock fine aggregate. The steel slag aggregates used by the Ministry were from Dofasco, Stelco, and Levy steel manufacturing plants, (with one small test section of Lasco slag). There were two different types of traprock used, 3 M Havelock and Armbro (Marmora). The blast furnace slag came from National Slag Limited.

Percentage Retained 4.75 mm Sieve

The study examines 88 job mixes over six years. There were 71 job mixes where DFC was designed at 45% retained 4.75 mm sieve; 67 by mass and 4 by volume. Of the remaining 17 job mixes, 13 were designed at 55% retained 4.75 mm sieve (only 12 built); 10 by mass and 2 by volume. The 4 remaining were designed by mass at 40% retained 4.75 mm sieve; all placed in 1980. The contracts with 55% retained 4.75 mm sieve were all placed after 1982. One of the mixes with 55% retained 4.75 mm sieve was changed to 45% in the field and no mix at 55% was placed. The two contracts with 55% DFC by volume were reruns of previous mixes with 55% by mass. Mix was placed for both types on the contract.

Asphalt Cement Content

The design asphalt cement content for the steel slag DFC mixes had a mean of 5.56% for 45% DFC mixes and 5.28% for 55% DFC mixes. For traprock mixes the mean asphalt content for 45% DFC mixes and 55% DFC mixes was virtually the same (4.42% and 4.44% respectively). The two contracts with blast furnace slags with steel slag fine aggregate require asphalt cement contents in the order of 6.9%. The one mix using dolomitic sandstone required 4.6% asphalt cement.

The small difference between asphalt cement contents for 45% and 55% mixes (i.e.+0.28% for steel slag and -0.02 for traprock from the overall average) is the result of a small population of 55% DFC mixes. Traditionally an increase in percentage retained on the 4.75 mm sieve from 45% to 55% reduces asphalt cement demand by about 0.5%.

Stability

The mean design stability for 45% DFC mixes using traprock was 15300 N and using steel slag was 20500 N. The mean design stability for 55% DFC mixes using traprock was 13900 N and using steel slag was 20700 N.

There were five contracts which had mixes at both 45% and 55% retained 4.75 mm sieve. As can be seen in Table 1 these contracts show that mixes with 45% coarse aggregate have a higher Marshall stability than the mixes with 55%.

TABLE 1: COMPARISON OF STABILITIES OF 45% and 55% DFC MIXES

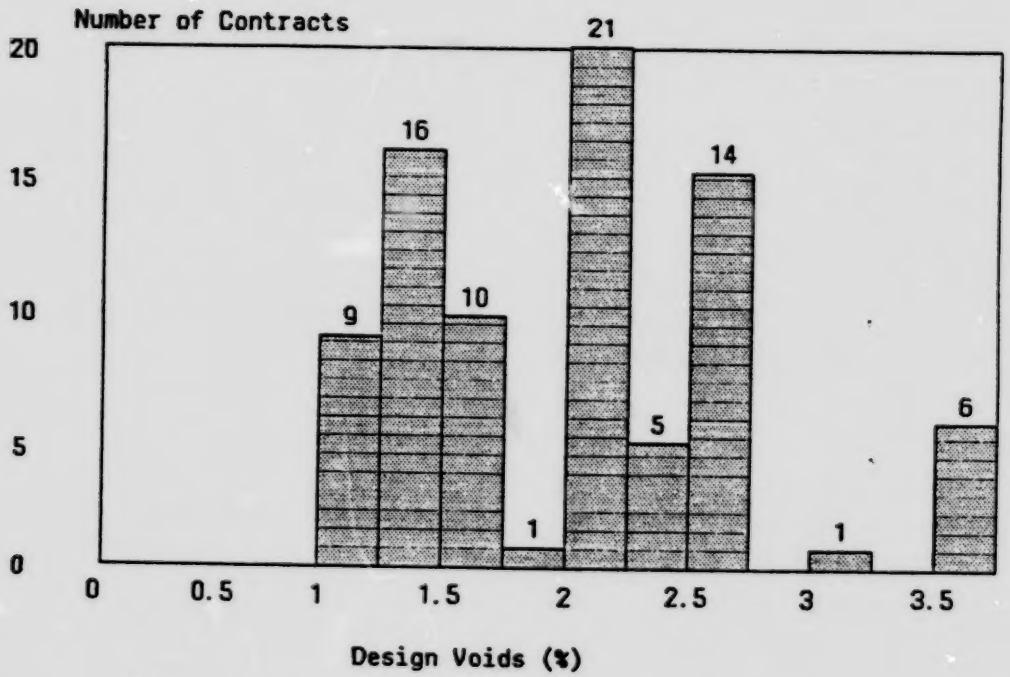
	Stabilities	
Contract	45% C.A.	55% C.A.
84-37	23,900	22,700
84-57	28,300	25,900
82-112	23,500	22,500
82-81 (f)	15,077	12,955
82-42 (f)	15,597	10,636

(f) represents field designed mixes and stabilities are mean values from plant checks.

Voids

The mean design void content for 45% DFC mixes using traprock was 1.7% and using steel slag was 2.0%. The mean design void content for 55% DFC mixes using traprock was 2.1% and using steel slag was 2.0%. Figure 1 is a histogram relating number of contracts and void contents. As indicated approximately 40% of the contract have design void contents between 1% and 1.75%. These contracts are mainly contracts with DFC on bridge decks where the pavement is designed with low voids to reduce permeability. Most of the balance of the contracts range between 2% and 2.75% voids with the exception of seven contracts. With the exception of these seven, the previous mixes were designed in accordance with OPS Special Provision 321 which specifies a target void content of 2.5%. The seven contracts with void contents in excess of 3% were early projects (1979 or prior). It would appear that these projects were designed in accordance to Marshall criteria for pavements (i.e. voids between 3% and 5%).

FIGURE 1: HISTOGRAM FOR DESIGN VOIDS



Percent VMA

For the DFC mixes evaluated there were two groups of percent VMA design values (See Figure E-7 Appendix E). The first small group had design percent VMA values between 16 and 20 and comes from pre-1980 contracts. These designs had coarse aggregate contents at or below 45% and all used steel slag aggregates. The second group is much larger and had design percent VMA values between 10 and 14%. This group reflects mixes of varying percent retained 4.75 mm sieve (i.e. both 45% and 55%) and different aggregate types.

Percent Passing 75 um Sieve

The mean percentage passing the 75 um sieve from the mix designs was 8.0% for 45% DFC traprock mixes and 4.9% for 45% DFC steel slag mixes. For 55% DFC mixes the mean percentage passing the 75 um sieve was 7.39% for traprock mixes and 4.1% for steel slag mixes. As expected 55% DFC mixes with less fine aggregate portion should have less percentage passing the 75 um sieve.

3.2 Design versus As Constructed

There are two sources of "as constructed" information which include laboratory plant checks (sometimes referred to as mobile laboratory plant checks) and acceptance testing (field laboratory). Not all contracts have data from both sources because on some contracts the laboratory plant checks were used as acceptance testing or on others there were no laboratory plant checks taken.

Percentage Retained 4.75 mm Sieve

To determine the difference between as constructed and design percentages retained on the 4.75 mm sieve, a 'Difference from Target' analysis was undertaken. Difference from target represents the difference between the design percentage retained 4.75 mm (i.e. target) and the actual mean coarse aggregate content as indicated by the laboratory plant checks or acceptance test results. Since the mathematical determination for the difference from target is the as constructed value minus the design value, a negative value indicates that design values were not obtained and a positive value indicates that design values were exceeded.

For 45% DFC mixes the mean difference from target for percent retained on the 4.75 mm sieve was +0.9% (standard deviation of 3.4%) for the laboratory plant checks and +0.8% (standard deviation of 3.8%) for the acceptance field tests. This would indicate there is a tendency for 45% DFC mixes to be constructed at slightly higher percent retained on the 4.75 mm sieve.

For 55% DFC mixes the mean difference from target for percent retained 4.75 mm was -1.8% (standard deviation of 2.2%) for laboratory plant checks and -1.9% (standard deviation of 3.3%) for field acceptance testing. This would indicate that the 55% DFC mixes are apt to have slightly less coarse aggregate than designed.

In Appendix E (Figure E-1) the difference from target for percent retained on the 4.75 mm sieve is portrayed for the plant checks and acceptance tests in a histogram format. It is apparent that there is a significant number of contracts where the mean coarse aggregate content from either acceptance samples or plant checks falls within the borderline to rejectable areas (i.e. deviation on the 4.75 mm sieve of more than 5% from design values). Most of the contracts having borderline to rejectable coarse aggregate content have small tonnage (average 1250 t) and generally do not have many tests (average of 5 plant checks and 5 acceptance tests per contract), therefore this conclusion may not be representative of all DFC pavements.

A cursory examination was undertaken to see if the fluctuations in coarse aggregate content were aggregate related. Figure E-2 in Appendix E would indicate, based on difference from target, that steel slag is slightly more variable than traprock. This is also confirmed in Table E-1 in Appendix E.

Asphalt Cement Content

A review of difference from target for asphalt cement content generally indicates that overall there is little divergance from the design values. The mean difference from target for 45% DFC is 0.00 (using mean plant check value) and for 55% DFC is 0.05 (Table E-2 Appendix E). The field acceptance testing indicates slightly higher values (i.e. 0.05 and 0.07 respectively. This information is presented in a histogram format in Appendix E, Figure E-3.

By aggregate type, there is a trend for traprock aggregates to have higher positive differences from target (i.e. test data higher than design) and steel slag to have negative difference from targets (Figure E-4 and Table E-2 Appendix E). This may indicate that there is more loss of fines in the "dirtier" traprock and that the steel slag is exhibiting high absorption of the asphalt cement which is not being recovered during the extraction test.

Stability

As indicated in Figure E-5 there is a tendency for stability values obtained from compacted Marshall field samples to be slightly lower than design values. The values for the moderately high stability mixes (10,000 to 20,000 N) are generally being met or exceeded in the field. The mixes with very high design stabilities (in excess of 20,000 N) are not exhibiting these high stabilities at the time of construction. It should be noted that virtually all DFC mixes exhibit stability well in excess of the minimum Marshall stability criteria (8900 N for 5000 AADT for two lanes).

The 45% DFC mixes show the overall trend described above. The 55% DFC mixes generally exhibit lower stability for compacted Marshall plate samples than designed.

Percent Voids

Upon examining the mean percent voids (compacted Marshall from field samples) versus design voids for each contract (Figure E-6 Appendix E), it can be seen that the in place mix voids tend to be higher than the design voids. All 55% DFC mixes demonstrated as constructed voids higher than designed.

Percent VMA

As described previously there are two groups of percent VMA data when comparing as constructed percent VMA to design percent VMA. For the group with design percent VMA between 16 and 20 the field values match the design values. For the larger second group with design values between 10% and 14% there is a general tendency for the values from the plant check samples to be significantly higher than design values.

The increase in percent VMA is related to observed increase in void contents from design to as constructed data. In addition, the design percent VMA calculations reflect absorption of the asphalt cement into the aggregate (formerly referred to as VMA #2). For many of the early plant checks, the VMA calculations did not reflect absorption of asphalt cement into the aggregate (formerly referred to as VMA #1). By nature of the calculation VMA #1 is higher than VMA #2 for the same mix.

Percent Passing 75 um Sieve

The difference in percent passing 75 um sieve caused by different aggregate types is readily apparent in Figure E-8 (Appendix E). The traprock aggregates with design percentages passing the 75 um sieve between 6.5% and 10% have plant check values slightly lower than the design values. This appearance that the design mixes have larger amounts passing the 75 um sieve than the actually constructed mixes may be a function of test procedures. For design, the percentage passing the 75 um sieve is determined by washing which is generally not undertaken on field samples. Washing produces higher amounts passing the 75 um sieve. The lower percent passing the 75 um sieve, for the plant checks may also reflect a loss of fines during hot mix production (i.e. use of a wet collector at the asphalt plant). There also may be some loss of fines during extraction of the asphalt cement.

The steel slag mixes have design percentage passing the 75 um sieve ranging from 2% to 5.5%. The values from the field checks for this group are approximately the same as design values. Given the lower quantity of steel slag passing the 75 um sieve, washing in the design stage would have less of a pronounced effect.

3.3 Discussion of Contract Data

The following points from the design data are noted for the 1979 to 1983 DFC mixes:

1) Most of the mixes examined were 45% DFC mixes.

2) Use of steel slag predominated over traprock. This trend is expected to continue.

3) For steel slag, 45% DFC mix designs required 0.28% more asphalt cement than 55% DFC mix designs. For traprock mix designs 45% DFC and 55% DFC required the same asphalt cement content.

4) All DFC mixes exhibit high to very high stability. The 55% DFC mixes exhibit lower Marshall stability than do the 45% DFC mixes. This phenomenon is a result of the limitations of the Marshall stability test procedure and will be addressed in more detail later in the report.

5) Most DFC mixes were designed with void contents in the order of 2.5% in accordance with OPSS Special Provision 321. Bridge deck mixes were designed with somewhat lower void contents (1% to 1.75%).

6) Most mixes were designed with percent VMA in the range of 10% to 14%. For some unexplained reason, a small group of early steel slag mixes at 45% retained 4.75 mm sieve had percent VMA in the 16% to 20% range.

7) Steel slag 45% DFC mix designs averaged 4.9% passing the 75 um sieve. Traprock 45% DFC mixes averaged 8.0% passing the 75 um sieve. DFC mixes with 55% passing have slightly less material passing the 75 um sieve.

The review of as constructed data versus design values indicates:

1) There is an overall tendency for 45% DFC mixes to be built with slightly higher percentage retained on the 4.75 mm sieve than designed. The 55% DFC mixes tend to have slightly lower coarse aggregate contents than designed. There is wider variations in coarse aggregate content on smaller contracts. Steel slag mixes are slightly more variable than traprock mixes.

2) Overall there would appear to be close conformence on asphalt cement between field values and design values, however there are two different populations. Traprock mixes show higher as constructed values than designed, while steel slag mixes show lower as constructed asphalt cement contents than designed. This trend is prevalent regardless of percent retained 4.75 mm sieve.

3) For 45% DFC mixes, design stability values are being attained for the moderately high stability mixes (10,000 N to 20,000 N) but the very high stability mixes (over 20,000 N) are falling short of design. For 55% DFC mixes generally exhibit slightly lower stabilities in the field than designed.

4) Both 45% and 55% DFC mixes generally show higher recompacted Marshall voids and percent VMA than design.

5) Traprock mixes generally show less percent passing the 75 um sieve in the field compared to design. This may be due to loss of fines in mixing or during the extraction test or design values being higher because of washing. The steel slag mixes have similar percentages passing the 75 um sieve in the field as in design.

4. PERFORMANCE AND MAINTENANCE PROCEDURES

A telephone survey of District maintenance staff was undertaken to determine the perceived performance and maintenance requirements associated with DFC pavements. The survey was undertaken in February and March 1985. All Districts where DFC was placed were surveyed. Maintenance Engineers and Supervisors were contacted first to gain an overall District perspective. Subsequently, twenty-one patrol supervisors were interviewed to obtain specific comments as to the maintenance procedures and performance of the DFC pavements in their respective patrols. Their responses are tabulated in Table F-1 (Appendix F). The breakdown of patrols and contracts is given in Table F-2 (Appendix F). Contact was also made with the City of Windsor to determine this information for the E.C. Rowe Parkway. The interviews were unformatted with general inquiries about the type of maintenance procedures for salting and sanding, permeability or any other related phenomenon. For the locations with steel slag aggregates, a specific question was asked to find out if lime leaching was a problem.

At the District level, all of the Maintenance Engineers and Supervisors could distinguish the differences between DFC and OFC and were familiar with most of the characteristics associated with DFC pavements. Of the twenty-one patrol supervisors contacted, all knew of friction mixes but approximately one-third of them did not know the difference between DFC and OFC. By and large most of these patrols would have DFC pavements only and would have limited involvement with OFC pavements.

The complete maintenance survey can be summarized as follows:

1) Patrols that use salt only generally apply the salt in windrows or with slow spinners.

2) Patrols using salt only had no icing problems or made no comment as to having these problems.

3) The general maintenance procedure for the balance of the patrols studied is to apply a sand mixture containing 15% salt using spinners and salt only for storms using spinners or placement in windrows. There are minor exceptions to this where there is either less salt in the sand or 30% to 50% salt content for storms.

4) Three of the patrol supervisors noted that double applications of salt and/or sand were generally required in the DFC sections.

5) Four of the patrols experienced icing problems only during the first winter. In all cases, the maintenance personnel were not informed of the placement of DFC pavement and that different maintenance procedures were required.

6) There was a wide range in the drainage characteristics of the DFC as perceived by the maintenance staff. The comments ranged from "looks and acts like an OFC" to "can't tell the difference between the DFC and an HL 3 pavement" (i.e. is permeable).

7) At the locations where there were open gravel shoulders, the DFC drained well with two exceptions where icing problems were encountered.

8) The DFC pavement has more spray than OFC as noted by three patrol supervisors.

9) Six patrols indicated that DFC iced faster than adjacent pavements.

10) Many areas experienced ravelling, either as potholes or at cracks and joints. The main reason indicated by the maintenance personnel for this ravelling was that the pavement was too thin.

11) A large number of patrols had cracks occur in the DFC pavement. The main reason noted for the cracking was that the pavement was too thin or that cracks formed over the joints in the concrete base.

12) Steel slag leaching was not identified as a concern of the maintenance staff.

13) Wheel rutting was identified at one location where it occurred almost immediately after the construction of the roadway.

4.1 Impermeable Pavements

Of the twenty-one patrol supervisors contacted, six have pavements that showed characteristics of an impermeable pavement. There are 15 contracts in these patrols. All of these contracts had 45% or less percent retained on the 4.75 mm sieve. The comments for the patrols having impermeable pavements are isolated from the overall survey in Table F-3 (Appendix F).

For the impermeable areas, the maintenance procedure generally consists of application of salt only in windrows or with slow spinners. This application is consistent with other impermeable pavements (i.e. HL1, HL3).

The use of salt only indicates sufficient traffic warrants for the 'Preferred Salt Option'. The Preferred Salt Option is the exclusive use of salt on high traffic volume freeways. The pavements do not exhibit the problems that are associated with permeable pavements such as icing, trapped water at curb/gutter or paved shoulders or retention of dampness. One patrol was an exception and had problems with icing the first winter but the voids seemed to plug subsequently.

4.2 Permeable Pavements

The balance of the areas (fully three quarters of the projects) were perceived as permeable and the commentary is detailed in Table F-4 (Appendix F). There was a wide range in maintenance procedures for these

areas. This probably reflects varying degrees of permeability. Maintenance varies from clear salt to sand with 15% salt content. Only for impermeable areas was a second application of salt/sand required.

Most of the areas that experienced problems the first winter were permeable pavements. Icing problems were identified on half of the permeable pavements.

4.3 Discussion of Maintenance Procedures

The maintenance survey indicates that many of the DFC pavements that have been placed are "dense" in name only and provide for varying degrees of permeability. Impermeable DFC pavements have maintenance procedures similar to other impermeable pavements (i.e. windrow applications of material). Even slightly permeable pavements are being treated effectively with windrow applications. As permeability increases the effective maintenance procedure becomes broadcasting of salt/sand and usually with higher applications of salt/sand.

From the maintenance survey it appears the lower the coarse aggregate content, the less permeable the mix. The four 40% DFC mixes and a small portion of the 45% DFC mixes were impermeable. For example, the City of Windsor reported that for the 40% DFC on the E.C. Rowe Parkway they couldn't tell the difference between it and an HL3.

However, most of the 45% DFC mixes and all of the 55% DFC mixes were permeable. Some of the 55% DFC pavements were perceived to be as permeable as OFC pavements.

5. EXAMINATION OF DFC PROPERTIES

5.1 Permeability

MTC has three different methods to test the permeability of pavements. The original method used was established by the Johns-Manville Company. This test measures the change in a falling head of water contained in a vessel approximately 150 mm in diameter with a sealed perimeter at the pavement interface. Pavements with values in excess of 0.42 cm^3/s (25 mL/min) were considered permeable. The Johns-Manville test is primarily used in the field. This test had been used up to 1983.

A second falling head test as detailed by the Federal Highways (Work) Administration (FHWA) was then employed by the Ministry. The FHWA test uses the same principles as the previous method but has a 63.5 mm diameter standpipe. This method can be used in the field or on core samples in the laboratory. For the FHWA test method, pavements with permeability values greater than 10^{-3} cm^3/s are considered permeable. This test is still being used by the Ministry for porous pavements. For comparison OFC pavements can exhibit permeabilities as high as 1 cm^3/s and traditional HL-1 pavements have permeabilities in the order of 10^{-4} cm^3/s.

The newest method in use by the Ministry is the measurement of air permeability of a pavement sample. This method uses a vacuum over a core sample to draw air through the sample. The rate of flow is measured by finding the volume of air flow over time, taking into account barometric pressure and temperature. For this method "permeable" pavements may exhibit readings as low as 10^{-9} cm^3/s of air. This test is primarily used for tight mixes which would otherwise be considered impermeable.

There has been limited correlation to date among the data obtained by each method. In addition, it should be noted that permeability is expressed in different units for each test.

Highway 401 from Dufferin St. to Highway 400

Permeability tests were conducted on the Highway 401 test sections (Contract 74-20) after 2 and 4 years of service, using the Johns-Manville method. For DFC sections 3, 7 and 9 it was found that they were all permeable after 2 years of service but somewhat less permeable than OFC sections. At four years the DFC mixes were all "impermeable" and the OFC mixes were still permeable (8). The pavements that were impermeable by the Johns-Manville test may well have demonstrated permeability if some other test had been used (i.e. FHWA permeability).

Highway 401 from Oshawa to Highway 115

As the result of severe icing that occurred on this section of Highway 401 during the winter of 1982-83 a coring program was initiated to determine permeability of the DFC pavement. The complete analysis is provided in Appendix G.

From the core data the following is apparent:

1) All DFC pavements on the Highway 401 between Oshawa and Highway 115 were permeable. Average permeabilities (FHWA test) ranged from 8.2×10^{-3} cm^3/s to 2.4×10^{-1} cm^3/s.

   There were four DFC pavements in this section of Highway 401. Two were designed at 45% retained 4.75 mm and two were designed at 55% retained 4.75 mm. These were built at 40.8%, 42.8%, 53.2% and 55.6% retained 4.75 mm respectively.

2) Permeability depends on in-place pavement voids which in turn relates to compaction and mix voids. (Figures G-1 and G-2). An increase in mix voids will increase in-place pavement voids which provides for increased permeability. Lower compaction provides for increased in-place voids and increased permeability.

3) Higher coarse aggregate contents provide for higher in-place pavement voids (and higher permeability) (Figures G-3 and G-5, Appendix G).

4) Higher coarse aggregate contents tend to contribute to lower compaction (Figure G-4).

5) The HL-4 shoulders are virtually impermeable (5×10^{-4} cm/s permeability) and act as barriers for water passing through the permeable DFC main lanes.

5.2 Friction Characteristics

To acquire friction information on DFC pavements, the computer listing of DFC contracts was reviewed by the Design Evaluation and Pavement Section. There were limited friction test results available. Those available are shown in Table 2. This table does not include friction data from the Lindsay test site or the Highway 401 Toronto By-Pass test sections. The majority of the contracts have adequate friction values.

TABLE 2: FRICTION TEST RESULTS

Contract	%C.A.	Year of Data	SN100 Km/h	SN80 Km/h
82-03	55 Traprock	1983	38	
80-55	45 Traprock	1983	38	
78-102	45 Traprock	1983		30
80-59	45 Steel slag	1983	33	
81-86	45 Steel slag	1982	27	
	45	1984	40	
80-67	45 Traprock	1983	35	
	45	1984	36	

As can be seen from Table 2 there is limited comparable information for 45% DFC versus 55% DFC. However visual review by the members of the Task Force on the Performance of Bituminous Friction Courses and subsequent visual review by Bituminous staff indicate that:

(i) The 55% DFC provides for a more rugose (deep surface) texture than the 45% DFC.

(ii) That in high traffic areas the macro-texture of the 45% DFC becomes immersed.

It should be emphasized that there have been no comparative controlled field installations constructed, therefore, these observations have not been supported by test data.

The relationship between coarse aggregate properties (i.e. type, size, shape, hardness and mineral composition) and the resulting surface texture has been well documented (4, 9, 10, 11,). Kamel et al (4) succinctly described the friction parameters of the aggregates. To have good friction characteristics the surface must exhibit both sufficient micro-texture and macro-texture. The macro-texture is a function of the physical properties of the coarse aggregate macro-projections such as height, width, angularity and density. Macro-texture is needed to break up the water film and to provide drainage of the bulk water from the tire/pavement contact area. Micro-texture is a function of the harshness of both the micro-projections of the matrix and the macro-projections. Micro-texture is required to penetrate the thin water film that exists on the roadway after drainage of the bulk water.

From selected data in the Ryell study (2) of the Highway 401 test sections it was attempted to determine the effects of macro-texture on the measured friction numbers. The selected data comes from Sections 1 to 10 passing and driving lanes which represents the densely graded friction mixes (i.e. HL1 and HL1 modified [DFC]). From the data, it would indicate that there is a linear correlation between the density of macro-projections and skid test trailer values for the initial survey ($r = 0.83$) and at 21 months

(r = 0.81). See Figure H-1, Appendix H. For the same sections and lanes there was a linear correlation between the height of macro-projections and the friction value (r = 0.64 initial and r = 0.71 at 21 months) as seen in Figure H-2, Appendix H.

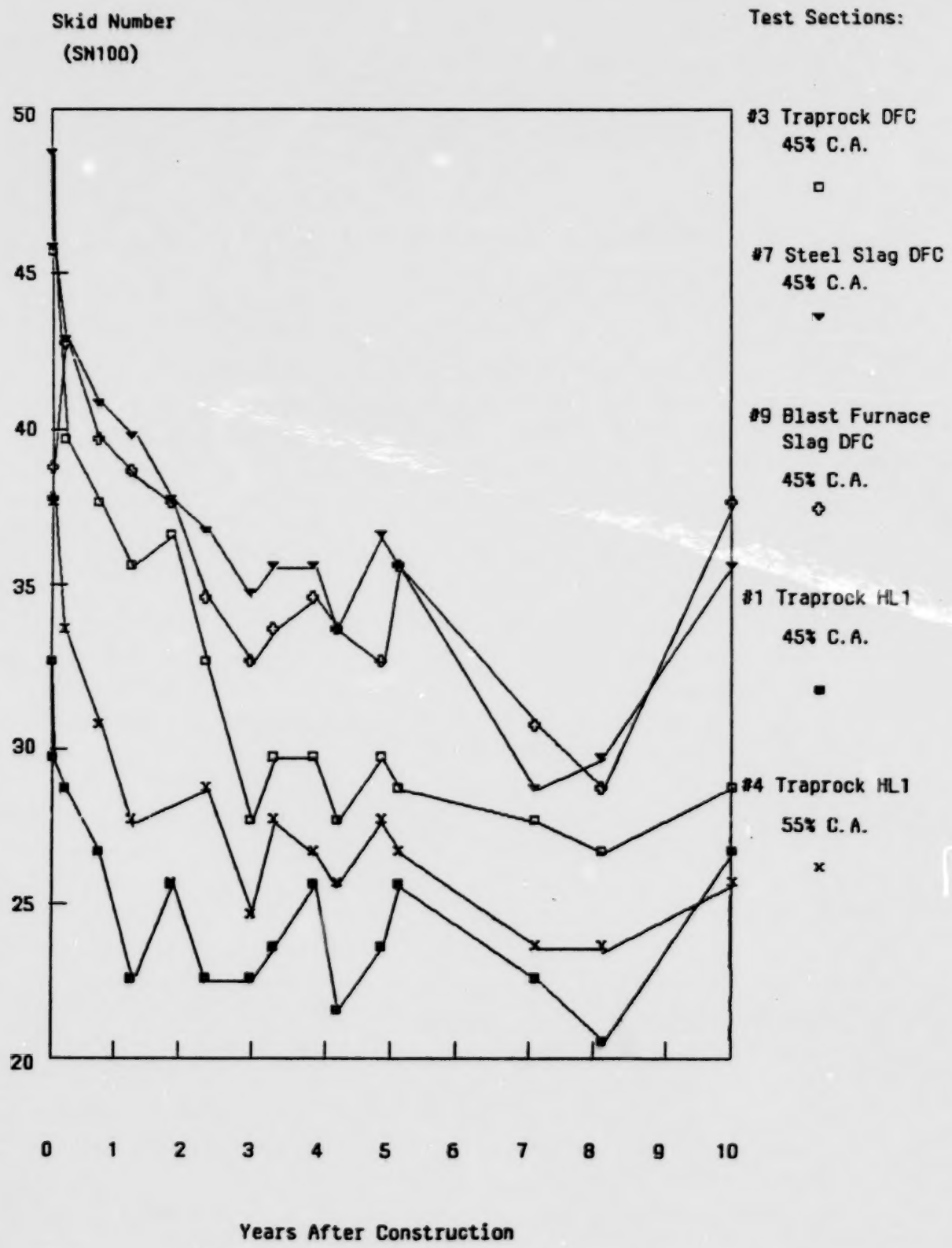
It should be noted that above findings are in disagreement with an unpublished study conducted by the Pavement Design and Evaluation Section (2) on selected Highway 401 sections (Sections 3, 7, 8, 9, 10, 14 and 19) which indicates that relationship between density of macro-projections and friction numbers as a curvilinear relationship. This work reports that friction numbers increase with an increase in macro-projection density up to about 48% macro-projection density. Beyond 48% macro-projection density the friction resistance drops off.

Highway 401 Test Sections

The 401 Toronto By-Pass test sections have had friction testing almost every year since construction. The friction values for test sections 3, 7 and 9 (DFC sections) are shown on the graph in Figure 2 on page 30. Test sections 3, 7 and 9 consist of traprock, steel slag and blast furnace slag coarse and fine aggregates, respectively. All three sections show good friction values. The superiority of the slag mixes over the traprock mix is quite evident from the difference in friction values shown on the graph.

Also in Figure 2, the superiority of higher coarse aggregate contents in HL1 mixes is demonstrated in the comparison of test section 1 (45% traprock coarse aggregate with 3:1 blend natural sand and limestone screenings) to test section 4 (55% traprock coarse aggregate with a 3:1 blend of natural sand and limestone screenings). For the initial four year period the 55% HL1 clearly demonstrates superior frictional qualities over the 45% HL1. Beyond the four year period, the friction numbers of the two sections converge and at points only differ by 2 which may not pose a significant difference in frictional characteristics. In spite of the convergence in numbers the 55% HL1 maintained higher friction numbers throughout. The last friction measurements are unexplained (i.e. higher values in test section 1 over test section 4).

Figure 2 : 401 Test Sections (Driving Lane)



The superiority of DFC mixes with premium fine aggregates (traprock screenings) over HL 1 mixes with the same coarse aggregate type and percent retained 4.75 mm is seen in the comparison of test section 3 and test section 1 in Figure 2. The DFC mix (section 3) maintained significantly higher friction numbers throughout the pavement life.

5.3 Discussion of DFC Properties

Since the approval of DFC for use on expressways there has been a general lack in accumulated test data for such things as permeability and friction measurements. This lack of information applies to both before and after the change in coarse aggregate content. There has been regular friction testing on the various test sections installed but limited testing on the larger full scale DFC contracts. To compound the problem no comparative controlled test sections of 45% DFC versus 55% DFC have been installed.

Early work indicated that DFC's plugged in a year or so. This plugging may have been the result of winter sand filling the voids. The plugging may have also been "apparent" and the result of the limitations in early Johns-Manville test in determining permeability on tighter mixes. Also, all mixes undergo some compaction with traffic, which would reduce permeability.

The FHWA permeability testing of Highway 401 from Oshawa to Highway 115 indicates that all DFC pavements in this stretch were permeable in 1983. These pavements have a range of in-place coarse aggregate contents ranging from 41% to 56%. District staff relate that there has been very little or no change in perceived permeability of these sections.

For the Highway 401 east of Oshawa, there was an increase in permeability as coarse aggregate content increased. This does not necessarily mean that 45% DFC mixes are impermeable and that 55% DFC mixes are permeable. All pavements in this section were permeable with the lower end (41% DFC) being slightly permeable and at the upper end the 56% DFC is performing like an

OFC. Elsewhere there are a few notable exceptions where the 55% DFC does not have the 'popcorn' appearance and the permeability associated with an OFC. DFC installations in Eastern Region in the vicinity of Ottawa (e.g. Contract 83-22) using dolomitic sandstone and Highway 7 east of Highway 404 in Markham (Contract 82-63) with traprock are examples. While these projects have exhibited some slight permeability there is general agreement among Region/District staff that permeability is not a problem in these sites. Definitely these 55% DFC pavements are <u>not</u> performing as OFC pavements. The various permeabilities of DFC mixes can be attributed to any or all of the following factors:

1) Percent Retained 4.75 mm Sieve

Permeability increases as coarse aggregate content increases . The increase may be a result of design (i.e. picking a 55% DFC rather than 45% DFC) or a result of construction tolerances.

2) Aggregate Properties

Traprock generally provides for tighter mixes than steel slag. Traprock aggregates have higher fines percentages passing the 75 um sieve, lower asphalt cement absorption and are less variable than steel slag which are all factors which provide for lower permeability. Lack of gradation requirements for steel slag fine aggregate and fluctuations in bulk relative density have contributed to the variable nature of steel slag. Given the ready availability of steel slag to the metropolitian Toronto market and its superior frictional qualities, steel slag will continue to be the predominate DFC aggregate, in spite of the nature of steel slag mixes to be more permeable than traprock mixes.

3) Lack of Field Adjustments to Mix Design

As indicated by the large shift in compacted Marshall voids from design voids, it would appear adjustments to mix designs are not generally being conducted by Quality Assurance staff. Often an adjustment to the mix design (e.g. an increase in A.C. content) is required to address a physical change in materials (e.g. loss in fines) that may occur during the mixing process.

4) Difficulty and Lack of Compaction

Stonier DFC mixes have a tendency to be harder to compact and that can account for higher permeability associated with them. In addition, a lack of compactive effort regardless of coarse aggregate content can provide for a permeable pavement.

5) Other Factors

Late fall paving can contribute to a very open permeable DFC. Drum mixers, particularly with wet wash systems, can cause a loss in percent passing the 75 um sieve and can also contribute to a more permeable mix.

The use of DFC in high speed, high traffic volume areas is valid. The DFC pavements have superior friction values to the HL1 pavements initially and retain this advantage throughout their life. The friction values in high speed locations appear to be closely related to the density and the height of the macro-projections (although studies elsewhere might indicate different).

Based on the Highway 401 test sections HL1 pavements with 55% coarse aggregate contents provide higher friction numbers (SN100) in the initial

period (4 years) over 45% HL1. The friction numbers (SN100) converge beyond that and differ at points by no more than 2 (which is not significant). Throughout, the 55% HL1 provides the higher friction numbers. It was the contention of the Task Force on the Performance of Bituminous Friction Courses and the Bituminous Section subsequently, that the rationale for DFC development should be based on, and extrapolated from, the Ministry's experience with HL1 mixes. It was felt that 55% DFC would certainly give the same initial superior frictional performance over 45% DFC (as did 55% HL1 over 45% HL1) and it was hoped that the convergence in friction numbers would be significantly less with 55% DFC than it was with 55% HL1.

6. 55% DFC VERSUS 45% DFC

To date, there have been no sections placed with controlled conditions that scientifically assess the performance difference between DFC mixes with 45% and 55% coarse aggregates. There have been several jobs where both 45% and 55% coarse aggregate DFC mixes have been placed. However deductions based on these are not valid because of uncontrolled variables and usual small portions of one mix (i.e. bridge decks).

The Task Force on the Performance of Bituminous Friction Courses examined the work by Kamel (Appendix C [7]) and field applications of the various mixes. With poor performance of some 45% DFC mixes (i.e. Highway 7 at Georgetown) and an empirical knowledge of mix design performance particularly with HL1 type mixes, it was felt that the coarse aggregate content should be increased from 45% to 55%.

Many points presented by Kamel are accepted by the authors and were confirmed during the course of this evaluation. Notably that:

1) 55% HL1 provides improved friction values (at least initially) over 45% HL1 based on test sections 4 and 1 of the Highway 401 test sections (Contract 74-20). (Refer to Appendix C and Figure 2).

2) Studies elsewhere indicated that optimum coarse aggregate content for deformation resistance was 55% for crushed aggregates. Japan had been employing high stone asphalt mixes (55% to 60%) primarily for excellent skid resistance characteristics and high resistance to rutting.

3) Asphalt mixes with higher stone contents require less asphalt cement.

Upon completion of this evaluation it is apparent that the physical properties of DFC are closely, although not exclusively, related to the percent retained on the 4.75 mm sieve. At the low end, DFC mixes with 40% retained on the 4.75 mm sieve are generally tight and perform similar to HL pavements. At the high end, in most cases, 55% DFC pavements exhibit permeability and can generally be considered to be acting as an "OFC". There are exceptions to both cases. Portions of Highway 401 from Oshawa to Highway 115 were built at about 40% retained 4.75 mm sieve and had the same permeability problems (water being trapped at impermeable shoulders) as did the rest of the sections. In Eastern Region, up until recently, they have had good success constructing relatively impermeable 55% DFC pavements with dolomitic sandstone. Contract 82-63, Highway 7 from east of Highway 404 in Markham using traprock is another relatively impermeable 55% DFC.

Between the extremes, 45% DFC exhibits a variety of characteristics. About one third of the contracts with 45% DFC have tight pavement. However the bulk of the contracts with 45% DFC are exhibiting some permeability.

DFC mixes with 55% coarse aggregate have other characteristics besides permeability that are similar to OFC mixes. As seen in Table 1, 45% DFC mixes generally have higher Marshall stability than 55% DFC mixes. A similar phenomenon is observed in Marshall stabilities of OFC mixes which are lower than dense graded mixes (3). This is not to imply that the high stone mixes are more subject to rutting, because the OFC performance to date does not substantiate that. Rather it shows that the load carrying mechanism for these stony mixes is different than for other mixes. For the stony mixes the stone on stone inter-skeletal interaction predominates. For the less stony DFC mixes the interaction is similar to other HL mixes with the coarse aggregate seated in a matrix of finer material. Lower stability values for higher stone content mixes may also indicate some limitations of the Marshall stability test for these type of mixes.

It should be recognized that the coarse aggregate content at which DFC mixes start to change their characteristics is not clearly defined. It becomes a function of other parameters, some mix related (amount passing 75 um sieve, overall gradation, percent A.C., etc.) and some construction related (compaction). Based on the evaluation in this report it can be

supposed that the 45% coarse aggregate DFC mixes approximate tight mixes and that many 55% coarse aggregate DFC mixes approximate OFC mixes. In resolution of the issue of the proper amount of coarse aggregate there is unfortunately no room for middle ground. Given the current Ministry acceptance criteria (i.e. acceptable range includes plus or minus 5% on the 4.75 mm sieve) then an intermediate mix design of say 50% retained on the 4.75 mm sieve could have acceptable ranges of material on the same contract from 45% to 55% coarse aggregate. These ranges would reflect pavements of low permeability to high permeability which would contribute to widely varied maintenance/performance characteristics. For mixes designed at 45% coarse aggregate there is the same magnitude of the range however the performance and type of maintenance procedures would be more or less the same for mixes from 40% to 50% coarse aggregate. The same would apply for mixes designed at 55% coarse aggregate (i.e. performance and maintenance procedures would be expected to be more or less the same for mixes with 50% to 60% coarse aggregate). The performance/maintenance would be distinct for each of the two groups.

6.1 Costs

DFC mixes with 55% coarse aggregate can be expected to use about 0.5% less asphalt cement than DFC mixes with 45% coarse aggregate. This represents a savings in asphalt cement of approximately $1.50 per tonne of DFC placed. However the coarse aggregate fraction costs in the order of $5.00 per tonne more than the fine aggregate fraction. Increasing the coarse aggregate content from 45% to 55% involves an increase in aggregate costs of about 50¢ per tonne of DFC placed. The net cost saving for 55% DFC over 45% DFC would be $1.00 per tonne of DFC placed or about 1.5%.

For the comparison of full width 55% DFC versus 45% DFC on the main lanes with HL3 paved shoulders, refer to Table 3 on page 38. As can be seen, the 45% DFC with HL3 shoulders is 13% less expensive than full width 55% DFC. In rural areas, where there are no paved shoulders, the cost comparison is one of 45% DFC versus 55% DFC.

TABLE 3: COSTS OF FULL WIDTH DFC

Costs estimated for Toronto (Highway 401 and Keele)

	1986 Costs (including AC)
3 lane 45% DFC with HL3 paved shoulder	(1) $104 000/km(2)
55% DFC full width	(1) $117 000/km(3)

1) 3 main lanes at 3.74 m each, paved shoulders 3.0 m each

2) DFC at $64/tonne density 108 kg/$m^2$ per 40 mm lift includes adjustments for A.C. and density, HL3 at $45/tonne 98 kg/$m^2$ per 40 mm lift.

6.2 Options

The viable options that currently exist as seen by the Bituminous Section are detailed in Table 4.

TABLE 4: OPTIONS FOR DFC

OPTION 1	-	Place existing 55% DFC full width using top of upper binder as drainage elevation (i.e. empties into gutters)
OPTION 2	-	Modify specifications and construction practice to provide for an impermeable 55% DFC and place it abutting lower cost paved shoulders or curb and gutter
OPTION 3	-	Place existing 55% DFC in areas of free drainage (open shoulder)
	-	Place existing 45% DFC in areas of restricted drainage (paved shoulder/curb and gutter)
OPTION 4	-	Place existing 45% DFC in all locations including abutting lower cost paved shoulders/curb and gutter
OPTION 5	-	Modify specifications and construction practice to provide for an impermeable 45% DFC and place it abutting lower cost paved shoulders/curb and gutter.

Discussion of the Five Options

Option 1

This option will address the concern of severe icing and water ponding at gutter edges and the interface with impermeable paved shoulders.

It does not require changes in the current specifications and construction practice.

DFC at 55% also results in excellent friction properties, minimizes immersion of the coarse particles into the mix and resists rutting.

Option 2

Realistically the restrictions that would be required to ensure an impermeable 55% DFC would be too prohibitive. This would require extremely tight restrictions on steel slag for gradation, absorption and bulk relative density as well as ensuring compaction requirements are met. The contracting industry would be required to provide hot mix within closer tolerances/acceptance limits than is currently the practice. On site monitoring for compactive effort would have to be enhanced. All Quality Assurance staff would have to be willing to make field mix design adjustments to compensate for any changes in voids etc... Developing a 55% DFC pavement that is impermeable is possible, but given current technology and the limitations it is not practical. In addition there is a large degree of risk; failure to provide any one of the criteria would probably result in a permeable pavement and potential repetition of the problems experienced on Highway 401 east of Oshawa.

Option 3

This option provides for application of 55% DFC and 45% DFC (possibly on the same contract). Difficulty in winter maintenance is anticipated. It also requires an impermeable 45% DFC in areas of restricted drainage (see discussion of Option 4).

Option 4 (and with Option 3 in restricted drainage)

The premise is that the 45% DFC will be impermeable or will lose what permeability it does possess after one winter. Evidence to date would indicate that while a third of the 45% DFC projects are impermeable, fully two thirds of the projects are permeable.

Option 5

To ensure that 45% DFC projects are impermeable would require similar restrictions (although not as strict) as outlined in Option 2. The 45% DFC could probably tolerate larger variations in gradation, bulk relative density of aggregates and percent retained 4.75 mm sieve than 55% DFC and remain more or less impermable. However, changes in the absorptive properties of the aggregates (which can be a problem with steel slag), unaddressed increases in mix voids in the field from design values, fluctuations in asphalt cement content, inadequate compactive effort or other factors like late fall paving can result in high permeability in either 45% DFC or 55% DFC. Lack of compactive effort is distinct from compactability. The 45% DFC mixes appear to have higher compactability than 55% mixes. To design an "impermeable" 45% DFC in areas of restricted drainage would require some revisions to current construction practices and materials specifications to insure that the pavement was indeed built impermeable. The risk associated with inadequately providing for one of these factors, while significantly less that of trying to build an impermeable 55% DFC, is still a concern. Portions of the Highway 401 east of Oshawa with 40% and 45% retained 4.75 mm sieve have demonstrated these permeability problems. While there is a cost saving (up to 13%) associated with placing 45% DFC against impermeable paved shoulders, there is significant concerns with creating permeability problems.

Therefore, the Bituminous Section recommends that DFC should be placed full width. (Note: after the Pavement Advisory Committee Meeting November 1985, this has been a requirement). To this end either Option 1 or Option 4 is the most desirable. Option 1 and Option 4 have the following in common:

1) They require no changes in aggregate types, combinations on specifications currently in use.

2) They tolerate the current level of compactive effort as supplied by the industry and the lack of field mix adjustment conducted by Quality Assurance staff.

3) Neither would necessitate changes in current acceptance criteria to provide for a more uniform mix.

4) They recognize that while it is probably in the Ministry's best interest to have impermeable DFC pavements that there are many factors affecting permeability. One or more of these factors can go awry and create permeability problems. Both options recognize the permeable nature of DFC pavements and design for it.

Ongoing improvements in any of the above areas will reduce permeability problems but neither option is predicated on the success of such improvements.

The comparison between Option 1 and Option 4 becomes the direct comparison between the relative merits of 45% DFC versus 55% DFC mix.

6.3 Benefits and Disbenefits 45% DFC versus 55% DFC

In Table 5 on page 42, the relative benefits/disbenefits of 45% DFC and 55% DFC are listed. The primary advantage to 45% DFC relates to the lower permeability associated with the mix. Given that at this time the requirements to ensure an impermeable 45% DFC mix are prohibitive and that full width DFC has been provided (i.e. drainage elevation taken as top of upper binder) then the importance of the permeability issue is diminished. The 45% DFC will in all likelihood require different maintenance procedures (broad-casting of salt/sand and higher concentrations of salt) than other HL pavements. As permeability in the DFC decreases performance/maintenance will closer approximate that of an HL pavement. The prime benefits of 55% DFC are the improved macro-texture (based on visual reviews) and lower unit cost due to lower asphalt cement content. The difference in maintenance procedures from other HL pavements is a drawback, particularly in rural areas; the 55% DFC can be anticipated to require different maintenance procedures throughout its service life.

TABLE 5: BENEFITS/DISBENEFITS 45% DFC versus 55% DFC

45% DFC

Benefits

1) Requires less coarse aggregate than 55% DFC (i.e. uses more steel slag fine aggregate of which there is a surplus quantity)

2) Less permeability than 55% DFC

3) Tends to have higher compactability than 55% DFC

Disbenefits

1) Probably should be placed full width. Unpredictable wide variations in in-place permeability due to variations in current materials /construction practice.

2) Depending on permeability will probably require different maintenance procedures from HL pavements

55% DFC

Benefits

1) Requires less A.C. than 45% DFC

2) Visual review indicates initial macro-texture superior to 45% DFC

3) Unit cost of 55% DFC is less than unit cost of 45% DFC (in excess of 2%)

Disbenefits

1) Must be placed full width, pavement will be permeable

2) Definitely requires different maintenance

Based on the above it is the recommendation of the Bituminous Section that the Ministry adopt:

i) the use of DFC full width and/or

ii) the use of DFC with 55% retained 4.75 mm sieve with the drainage elevation taken as top of upper binder through urban sections (top of upper binder placed flush with the top of gutters). DFC can be either ramped down at the outside edge(s) to meet the front face of the gutters or placed over the gutters as per OPSD-602.01.

7. OTHER ISSUES

During the course of this investigation several issues not directly pertaining to the 45% DFC/55% DFC issue but rather with regards to DFC in general were identified.

These include:

1) There is concern among Maintenance staff that the extra costs associated with maintaining DFC may not warrant the benefits over other mixes. During the evaluation of the test sections maintenance costs have not been a factor.

2) As DFC expands to the areas where there are insufficient traffic warrants (e.g. Highway 401 from Port Hope to Quebec border) there appears to be more opportunity for problems. DFC seems to be a mix that performs well in heavier trafficked areas but may have some problems in the rural areas. Given some success with HL1 Modified mixes (i.e. mixes midway between DFC and HL1) in Port Hope or the HL3 Modified mixes in Eastern Region, possibly comparisons with DFC should be undertaken.

3) Given that full width DFC was being considered due to the permeability problem, a cost comparison of OFC and DFC is in order. This comparison is detailed below in Table 6.

TABLE 6: COSTS OFC versus DFC

Costs Estimated for Toronto (Highway 401 at Keele St.)

	Esitmated Cost Per Tonne (1986)	Estimated Cost per Square Meter (1986)
DFC (1)	$64	$6.91
OFC (2)	$70	$4.46

(1) Density of 108 kg/m^2 per 40 mm lift with 4.5% A.C.

(2) Density of 63.75 kg/m^2 per 25 mm lift with 5.1% A.C.

Note that OFC pavements can be considerably less expensive (per square meter) than DFC pavements. This cost saving is primarily due to the reduced thickness that OFC pavements are placed at (25 mm versus 40 mm). These costs are somewhat misleading in that it is current Ministry procedure to not assign any GBE (Granular Base Equivalency) strength to the OFC pavement. The OFC pavement is considered to act only as a drainage and friction layer and contributes no strength to the pavement structure. The DFC is considered to perform like most hot mixes and contributes to the pavement structure (GBE = 2). For new construction where OFC is to be placed the binder course depths are normally increased to compensate for this, whereas this is not required for DFC pavements.

8. CONCLUSIONS

1) Most Dense Friction Course pavements are "dense" in name only and exhibit varying amounts of permeability.

2) No comparative field test sections have been installed that scientifically assess the difference in performance between 45% DFC and 55% DFC. However visual observations by the Task Force on the Performance of Bituminous Friction Course and subsequently by the Bituminous Section indicates that 55% DFC provides superior macro-texture over 45% DFC.

3) DFC physical properties are closely related to coarse aggregate content. The higher the percent retained on the 4.75 mm, the more likely the mix is to have a higher in-place void content and a higher permeability. There is a trend that stonier DFC mixes are harder to compact and have inherently higher mix voids.

4) 55% DFC mixes constructed with current practices are generally permeable and should be designed full width, like OFC pavements.

5) Maintenance staff have mixed reviews on the performance of 45% DFC abutting impermeable paved shoulders or concrete gutters. Depending on actual mix proportions, (asphalt cement content, coarse aggregate content), aggregate type, compaction etc... the 45% DFC may perform as a tight HL pavement or exhibit permeability.

   The tighter 45% DFC can be placed effectively against paved shoulders or concrete gutters. The permeable 45% DFC mixes as a rule cannot, although the mixes with slight permeability may plug after a winter or two.

6) While it may indeed be possible to develop impermeable DFC pavements there would have to be several revisions to current construction practises. These could include:

(i) Lowering percent retained 4.75 mm sieve (possibly to 40%)

(ii) Higher awareness and willingness among Quality Assurance staff to make adjustments to field mix designs to compensate for observed increases in voids from mix design values

(iii) Tighter acceptance limits on coarse aggregate (and possibly asphalt cement content) to provide for a less variable product

(iv) Closer monitoring and improved compactive effort by the Contractor

(v) Tight restrictions on aggregate characteristics such as gradation, absorption, and bulk relative density. This may result in the prohibition of the use of steel slag for DFC pavements

(vi) Other construction restraints such as no fall paving or the non-use of drum mixers for DFC.

Failure to provide for any of the above may result in a permeable DFC pavement. Recognizing the prohibitive nature of the restrictions, the Ministry should be recognizing the probability that most DFC pavements will be permeable to some extent and providing for full width drainage.

7) Winter maintenance demands of permeable DFC pavements are different from other HL pavements. Notably broadcasting of salt/sand is generally required, higher salt/sand ratios and occasionally double applications of material. The most effective maintenance procedure will be a function of pavement permeability.

8) Early permeability testing had indicated that voids in DFC pavement plugged with sand after a year or two. While some of the 45% DFC mixes with slight permeability have plugged, many 45% DFC remain permeable. The 55% DFC pavements can be expected to remain permeable throughout their service life.

9) A history of poor communications has been associated with DFC installations. On several occasions DFC pavement was installed and the patrol staff received no warning in advance of the special maintenance requirements. In the case of Highway 401 east of Oshawa in Port Hope District when the severe icing problems were encountered there was a general lack of established documented maintenance procedures. The District was left to trial and error or by word of mouth to develop effective maintenance techniques.

   DFC installations at the end of patrols and in isolation may pose specific maintenance problem areas where the patrol has to plan for different maintenance techniques for neighbouring pavements.

   Also, the different icing performance of the pavements may lead to surprise amoung the motorists, as they pass from one pavement to another.

9. RECOMMENDATIONS

1) DFC pavements should be placed full width or draining into concrete gutters (i.e. drainage elevation should be taken as top of upper binder course and the DFC should be either ramped down on the outside edge(s) to meet the front face of the gutters or placed over the gutters as per OPSD-602.01).

2) The Bituminous Section should establish test sections of 45% DFC and 55% DFC to assess the performance of the two mixes. In the interim DFC pavements should continue to be designed with 55% retained 4.75 mm sieve (by volume).

3) Maintenance Office should review and establish appropriate winter maintenance procedures for DFC.

4) Optional use of DFC with 45% retained 4.75 mm sieve on bridge decks should be permitted. The use of these mixes to prevent the intrusion of water would normally be initiated by the Regional Geotechnical Section. Should specific mixes for bridge decks be deemed necessary then air void contents of 1 to 1.5 percent should be targets for mix design.

5) DFC placement should be sequential from one contract to another whenever possible. DFC installations in isolation at the end of patrols should be avoided. Where DFC pavement is placed in isolation (i.e. black spot treatments, intersection improvements) the mix should have 45% retained 4.75 mm by volume. All resonable attempts should be made to provide an impermeable pavement.

6) Bituminous Section should continue work into:

   (i) correlation of different permeability tests

(ii) the development of new techniques and equipment for providing impermeable DFC pavements

(iii) the developments of porous open graded shoulder mixes using lower cost aggregate

7) Maintenance staff should be informed of the placement of DFC, particularly in those areas where it will be isolation. This notice should provide sufficient lead time to allow for the planning of proper maintenance procedures.

8) The findings of this report should be reviewed in conjunction with the ten year evaluation of the Highway 401 test sections between Dufferin Street and Highway 400 currently being undertaken by the Bituminous Section.

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1. Smith, P. and Schonfeld, A., 'Studies of Studded-Tire Damage and Performance in Ontario - Winter 1969-70', D.H.O. Report Number RR165, August 1970.

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3. Kamel, N., Corkill, J.T. and Musgrove, G.R., 'Bituminous Friction Course Sections at Lindsay, Ontario', Ministry of Transportation and Communications, Ontario. Presented at the 25th Annual Meeting of the Canadian Technical Asphalt Association, Victoria, B.C., November 24-26, 1980.

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7. Kamel, N., Internal Memo Re: 'Proposed Changes to the Design of HL1 and DFC Mixes and to Directives C-16', Project 24131, August 21, 1980. (Appendix C).

8. McDougall, J.I., Internal Memo Re: 'Permeability Tests, Contract 74-20, Highway 401, W/B Core Experimental Sections', June 13, 1979.

9. Emery, J.J., Lee, M.A. and Kamel, N., 'Skid Resistance Predictive Models for Asphaltic Concrete Surface Courses', Pavement Surface Characteristics and Materials, ASTM STP 763, C.M. Hayden, Ed., American Society for Testing and Materials, 1982.

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12. Musgrove, G., 'Skid Resistance Performance of Slag Pavements in Ontario', Engineering Materials Office, April 1981, Unpublished.

APPENDIX A

DENSE FRICTION COURSE
PERCENT RETAINED

memorandum

Ontario

To: Messrs.: P.F. Weber,
T. Kazmierowski,
P. Ksenych,
P. Korpal,
P. Arkema,
D. Mullett,
R. McLuckie,
Geotechnical Section,
Central Region.

Date: 83-06-14

RE: Dense Friction Course

Until the Bituminous Section, E.M.O. completes a review of the problems associated with the presently recommended 55:45, by volume, D.F.C. mix design, please ensure one of the following is carried out on present designs:

(i.) Change to a 45:55, by weight, D.F.C. mix.

(ii.) Ensure the 55:45, by volume, D.F.C. mix design is placed full width including shoulders and that positive lateral drainage can be obtained.

RDG:saw

R.D. Gunter
Head, Geotechnical Section

c.c. D. Brohm
D. Lynch
H. Chyc
B. Black
C. Rintoul
W. Sturdy

APPENDIX B

HIGHWAY 401 TEST SECTIONS

Table B2: Highway 401 Test Sections Friction Resistance Data

Test Section Number	Mix Type	Driving Lane				Centre Lane				Passing Lane			
		50 km/h		100 km/h		50 km/h		100 km/h		50 km/h		100 km/h	
		Initial	4 years	Initial	4 years	Initial	4 years	Initial	4 years	Initial	4 years	Initial	4 years
1	HL1	51	29	32	21	49	31	36	22	49	34	36	26
2	HL1	50	31	34	21	50	33	35	24	51	35	38	28
3	HL1	60	34	45	27	62	34	47	28	63	40	47	33
4	HL1	54	31	37	25	55	32	39	25	57	36	40	30
5	HL1	48	33	31	24	47	32	31	24	50	35	40	29
6	HL1	48	34	37	29	48	33	38	28	50	37	37	31
7	Mod. HL1	62	41	48	33	61	40	46	31	63	44	49	35
8	Mod. HL1	61	34	38	27	57	33	33	27	60	35	36	23
9	Mod. HL1	50	40	37	33	52	40	38	34	57	42	40	35
10	Mod. HL1	48	33	37	25	48	33	38	27	50	38	37	31
11	Sand Mix	50	38	38	28	50	37	41	29	54	41	40	31
12	Sand Mix	45	35	29	27	49	38	38	28	51	41	30	30
13	Open Graded	43	33	42	29	45	33	43	29	51	37	41	32
14	Open Graded	41	33	37	30	44	33	40	29	45	38	38	31
15	Open Graded	51	34	40	26	44	34	43	27	58	40	44	31
16	Open Graded	47	35	37	27	50	38	41	28	54	41	41	29
17	Mastic	41	31	28	27	40	32	30	28	37	34	28	25
18	HL1	43	29	33	20	41	30	33	21	46	33	30	25

Taken from "Skid Resistance of Bituminous Pavement Test Sections Highway 401 Toronto By-Pass", (2)

Adjacent concrete pavement demonstrated friction value of 18 at 100 km/hr

Table B1: Highway 401 Test Sections Mix Compositions

Test Section Number	Mix Type	Mix Composition % Wt. of Aggregate Plus Filler: Coarse Agg. Ret. No 4	Fine Agg. Pass No 4	Filler Material	* % Ret #4	Asphalt % Wt. of Mix	Mix Characteristics: Marshall Stability	Marshall Flow	V.M.A. % Vol.	Voids % Vol.	
1	HL1	45TR	41NS		43.8	5.4	1625	10.3	16.9	2.8	L
			14LS			5.4	2614	11.6	17.5	3.7	F
2	HL1	45TR	41NS		48.2	5.4	1625	10.3	17.2	3.0	L
			14TRS			5.3	2270	13.4	15.0	0.8	F
3	HL1	45TR	55TRS		47.5	4.1	3185	16.5	12.9	1.2	L
						4.0	3407	15.3	13.5	2.0	F
4	HL1	55TR	34NS		54.1	4.8	1720	10.2	16.0	2.7	L
			11LS			4.8	3027	12.3	14.2	1.2	F
5	HL1	60TR	28NS	2ASB	58.1	5.6	1800	15.0	14.2	1.0	L
			10LS			5.7	1903	22.5	16.0	0.9	F
6	HL1	60TR	38TRS	2ASB	62.3	5.3	2190	22.7	15.2	1.0	L
						5.4	2570	18.7	18.6	3.4	F
7	Mod. HL1	45SL	55SLS		46.8	5.3	3520	16.0	18.5	2.7	L
						5.2	3640	13.2	18.7	3.3	F
8	Mod. HL1	50SL	38NS		47.1	5.7	2160	12.9	17.3	2.3	L
			12LS			5.7	2990	13.7	17.7	1.9	F
9	Mod HL1	45BF	55BFS		43.2	8.0	2830	12.8	24.0	6.9	L
						7.8	3226	14.9	23.1	6.1	F
10	Mod. HL1	40BF	45NS		40.5	6.8	1975	10.4	17.9	2.9	L
			15LS			6.5	3155	9.7	17.0	2.2	F
11	Sand Mix	14TR	84TRS	2ASB	5.4	7.1	2084	27.2	17.7	0	L
						7.0	2175	40.2	19.5	0.2	F
12	Sand Mix	9TR	89TRS	2ASB	6.9	7.0	2650	19.2	16.8	0	L
						7.2	1885	45.1	20.7	1.1	F
13	Open Graded	67TR	33TRS		60.5	5.9	1458	12.7	20.8	4.7	F
14	Open Graded	67TR	31TRS	2ASB	71.7	5.8	1691	11.9	19.8	4.0	F
15	Open Graded	30TR	70TRS		29.3	5.8	2678	19.2	16.3	0.7	F
16	Open Graded	30TR	68TRS	2ASB	31.4	6.8	2116	30.5	18.6	0.2	F
17	Mastic	70TR	19TRS	9MF 2ASB	75.2	7.5	1887	56.7	21.0	1.0	F
**1-19	HL1	45TR	41NS		47.4	5.4	1625	10.3	16.9	2.8	L
			14LS			5.4	2825	14.5	14.6	0.4	F

* Based on field laboratory extraction tests.

** As Test Section 1 but constructed over a 1½" thick bituminous base course layer.

LEGEND

Coarse Aggregate
TR - Traprock
SL - Steel Slag
BF - Blast furnace Slag

Fine Aggregate
SLS - Steel Slag Screenings
LS - Limestone Screenings
TRS - Traprock Screenings
BFS - Blast Furnace Screenings
NS - Natural Sand (Glacial Deposit)

Filler Material
ASB - Short Fiber Asbestos
MF - Mineral Filler (Finely Crushed Limestone)
L - Laboratory Mix Designs
F - Field Laboratory Tests

Taken from "Skid Resistance of Bituminous Pavement Test Sections Highway 401 Toronto By-Pass", (2)

APPENDIX C

FRICTION

Ontario

To: Mr. D. F. Lynch,
Head, Bituminous Section.

Date: 80 08 21

Project: 24131

From: Research and Development Branch

Re: Proposed Changes to the Design of HL1 and D.F.C. Mixes and to Directive C-16

The proposed changes which were detailed in my memo of 80 05 26 are based on the performance to date of the various test mixes constructed on Highway 401, Toronto Bypass in 1974 and in 1978.

Figure 1 shows the high-speed skid resistance "SN_{100} km/h" versus pavement age for two HL1 test mixes "#1 and #4 of the 18 experimental mixes" with 45% and 55% coarse aggregate (i.e. Ret. #4). The superiority of the mix with 55% C.A. is quite clear. This mix provided and maintained skid resistance levels 4 to 5 skid numbers higher than that of the traditional HL1 mix. The improved skid resistance levels appear due to higher resistance to immersion of the macrotexture stone projections into the matrix under the heavy truck traffic.

Figures 2 and 3 show the change in texture depth and stone projections density with time for the two mixes. The mix with 55% stone content provided and maintained a reasonable macrotexture depth and macro-projection density on the pavement surface, whereas the macrotexture on the traditional HL1 mix has virtually disappeared after less than two years in service.

Similar observations are also noted for the two steel slag test mixes with 45% and 55% coarse aggregate content, see Figure 4. There appears that the use of high coarse aggregate percentages result in mixes with greater aggregate interlock which maintain better and longer lasting surface texture and skid resistance properties.

Results of laboratory testing on mixes with various coarse aggregate content in England reported by Dr. Fabb in the last C.T.A.A. meeting showed the optimum coarse aggregate content for deformation resistance to be approximately 55% for crushed aggregate and 45% for polished

gravel (Dr. Fabb's figure is attached). This seems to confirm our findings with HL1 and D.F.C. mixes with 55% stone content.

In Japan, asphalt mixes with 55% - 60% stone content are currently used on the primary highway system (T.R.B. circular #192, Feb. 1978). This change has been prompted by the excellent skid resistance characteristics and the high resistance to rutting of these mixes, particularly on heavy traffic routes when compared with conventional designs.

The use of asphalt mixes with such high stone content also has economic advantages. As shown in Table I, stonier mixes would require 0.5% to 0.6% asphalt less than traditional mixes. This represents a saving of approximately 10% of the required asphalt. In addition the improved texture and skid resistance qualities would mean a potential for wide use on facilities with A.A.D.T. in excess of 5000 per lane (which is now the limiting traffic criterion in Directive C-16). This means considerable construction cost savings because local fine aggregate may be used and less asphalt required. Cost figures provided by the Estimating Office indicate that an HL1 mix with 55% C.A. and local fines would cost approximately $2.25 per ton less than that of a D.F.C.

Handwork would be more difficult to carry out with the stonier mixes. On the overall, however, no unusual construction problems should be encountered, and with the use of local fines, no problems should be expected in achieving compaction levels comparable with normal HL1 mixes, see Table 2.

Our recommendations with regard to the limiting traffic criterion for the "new" HL1 design is based on a 5-year performance history of this mix on Highway 401, Toronto Bypass. Figure 5 shows the skid resistance performance versus accumulated equivalent traffic for both conventional and "stonier" HL1 mixes. Based on a desirable terminal skid resistance range of between 28 to 31, the useful life of this mix, from a skid resistance standpoint, is 20 million accumulated equivalent vehicles or an A.A.D.T. of 7500 with 15% commercial vehicles or 6500 with 20% truck traffic.

We shall aim to finalize these proposals so that our joint recommendations may be made to the Pavement Selection Committee at the earliest possible time.

I trust the above will be satisfactory and shall be glad to discuss it with you if you so desire. If in the meantime, further information is required, please let me know.

Nabil Kamel,
Research Officer.

Attach.
c.c. J. McDougall
P. Ksenych

TABLE I - Mix Composition and Design Asphalt Content for Mixes with 45% and 55% Stone Content

Mix Type	Coarse Aggr. Type & %	Fine Aggr. Type & %	Asphalt Content by Wt. of Mix	Remarks
HL1	45% Trap-rock	55% blend of sand & local screenings	5.4%	Test mix #1, 1974, Hwy. 401, Toronto
HL1	55% Trap-rock	45% blend of sand & local screenings	4.8%	Test mix #4, 1974, Hwy. 401, Toronto
D.F.C.	45% Steel slag	55% Steel Slag Scr.	5.3%	Test mix #7, 1974, Hwy. 401, Toronto
D.F.C.	55% Steel slag	45% Steel Slag Scr.	4.8%	Test mix #2, 1978, Hwy. 401, Toronto

TABLE 2 - Pavement Core Sample Tests

Mix Type	Pavement Voids, %		% Compaction	
	3 mo.	21 mo.	3 mo.	21 mo.
HL1 (45% C.A.)	5.6	3.7	94.4	99.5
HL1 (55% C.A.)	5.3	2.5	95.9	99.1

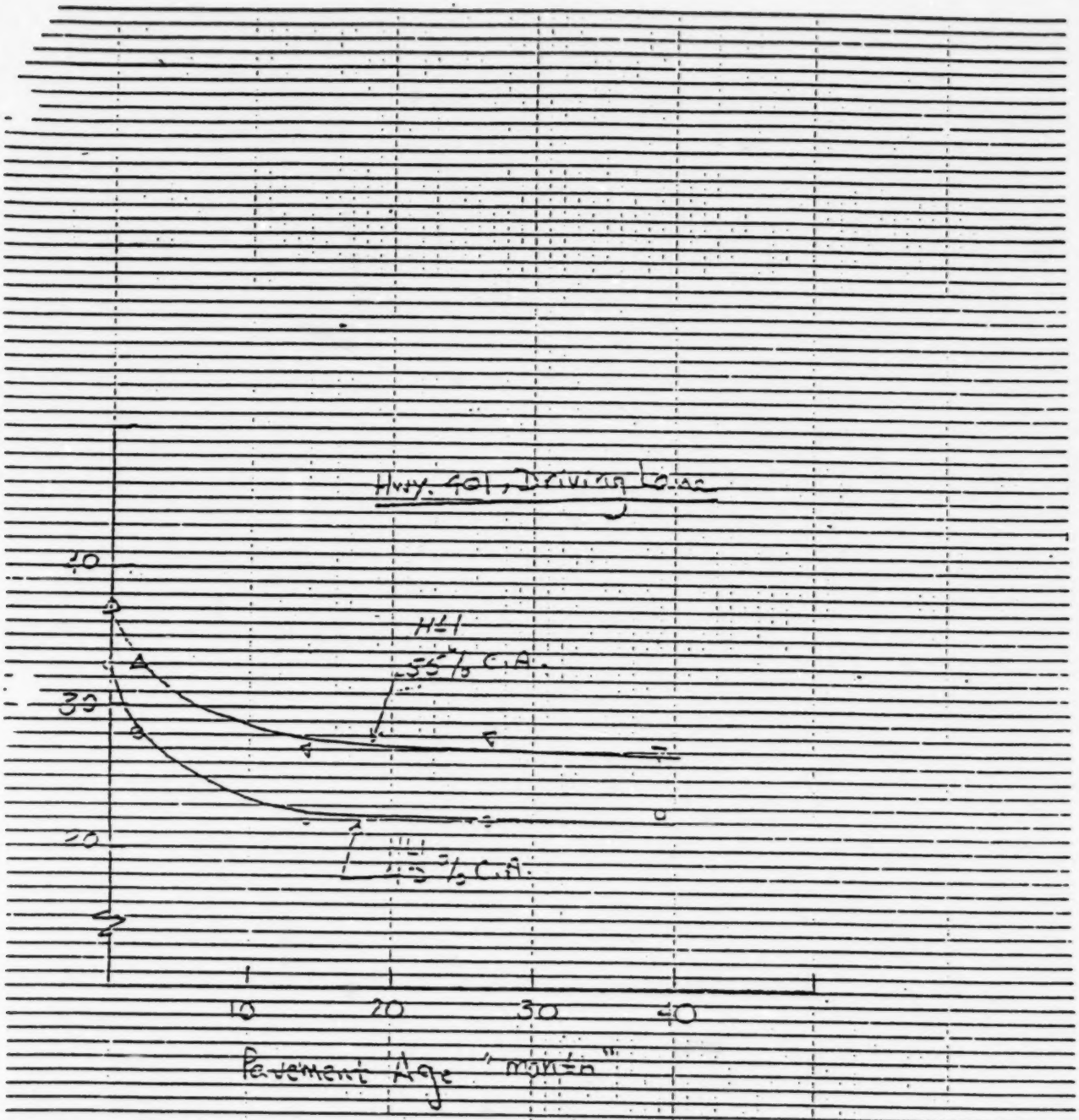

Hwy. 401, Driving Lane
40
35
30
20
H=1
35% C.A.
H=1
15% C.A.
10
20
30
40
Pavement Age "months"

Figure 1

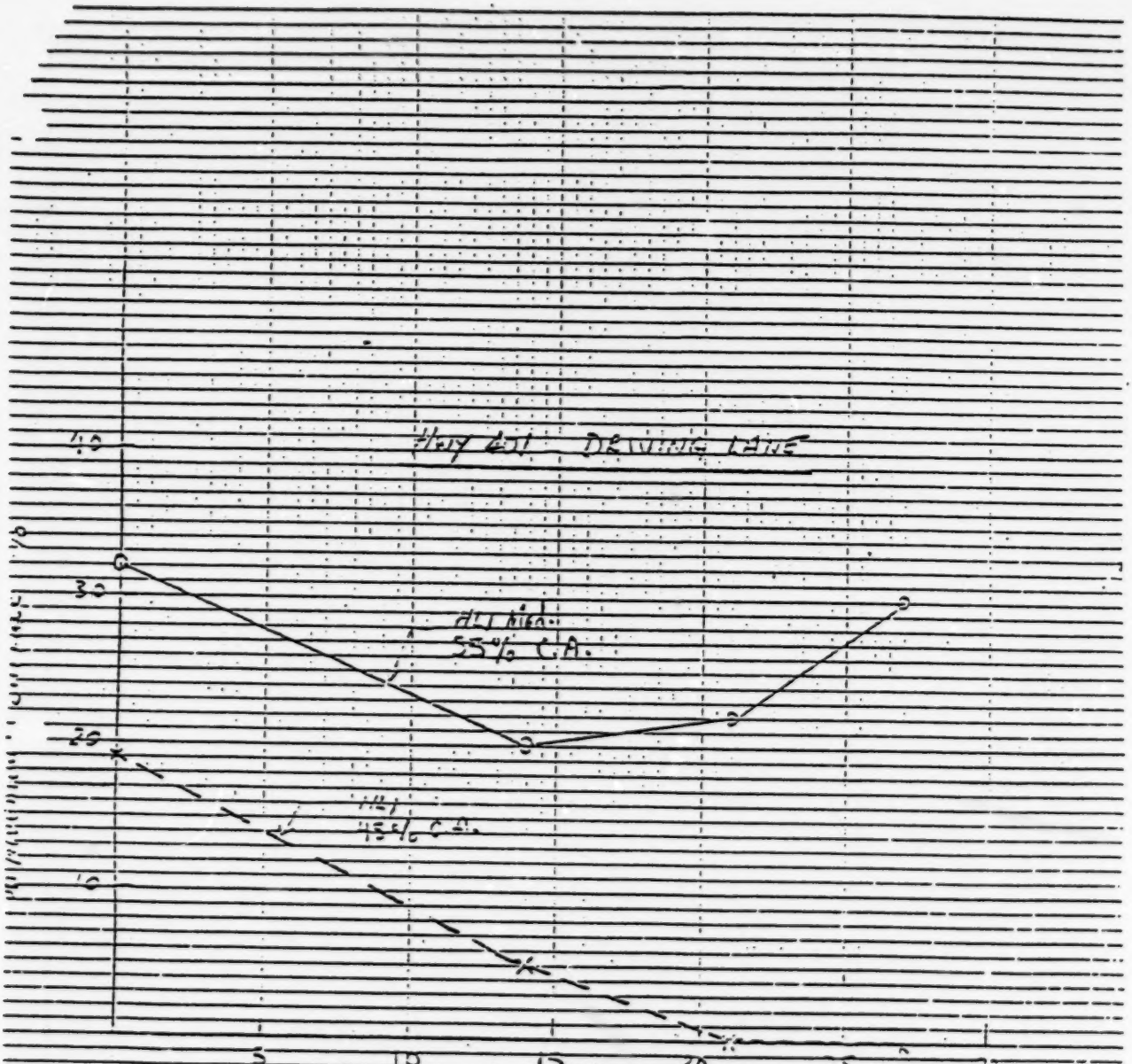


Figure 2

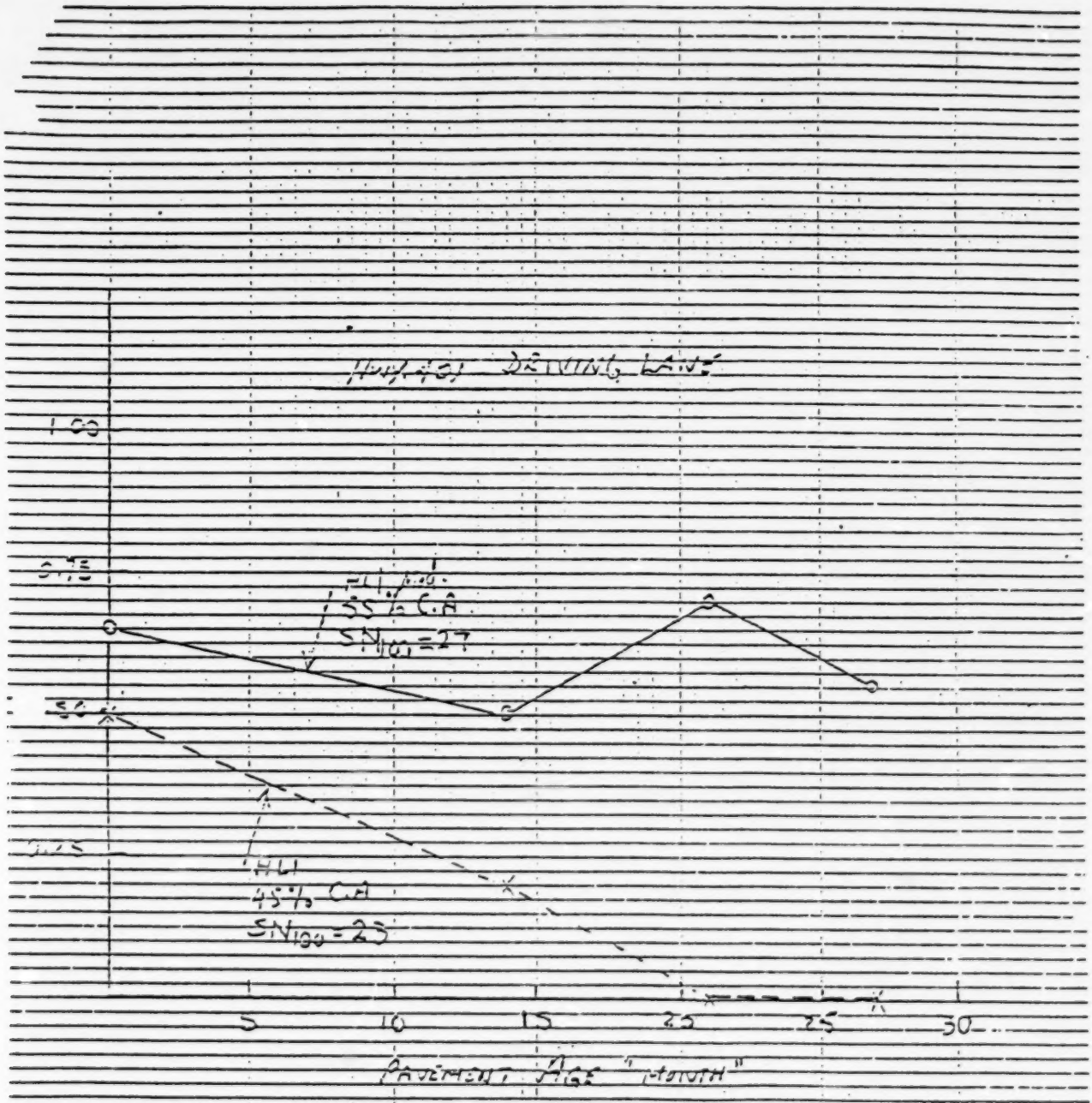

100
50
HL1
55% CA
SN100=27
HL1
45% CA
SN100=23
5
10
15
20
25
30
PAVEMENT AGE "MONTH"

Figure 3

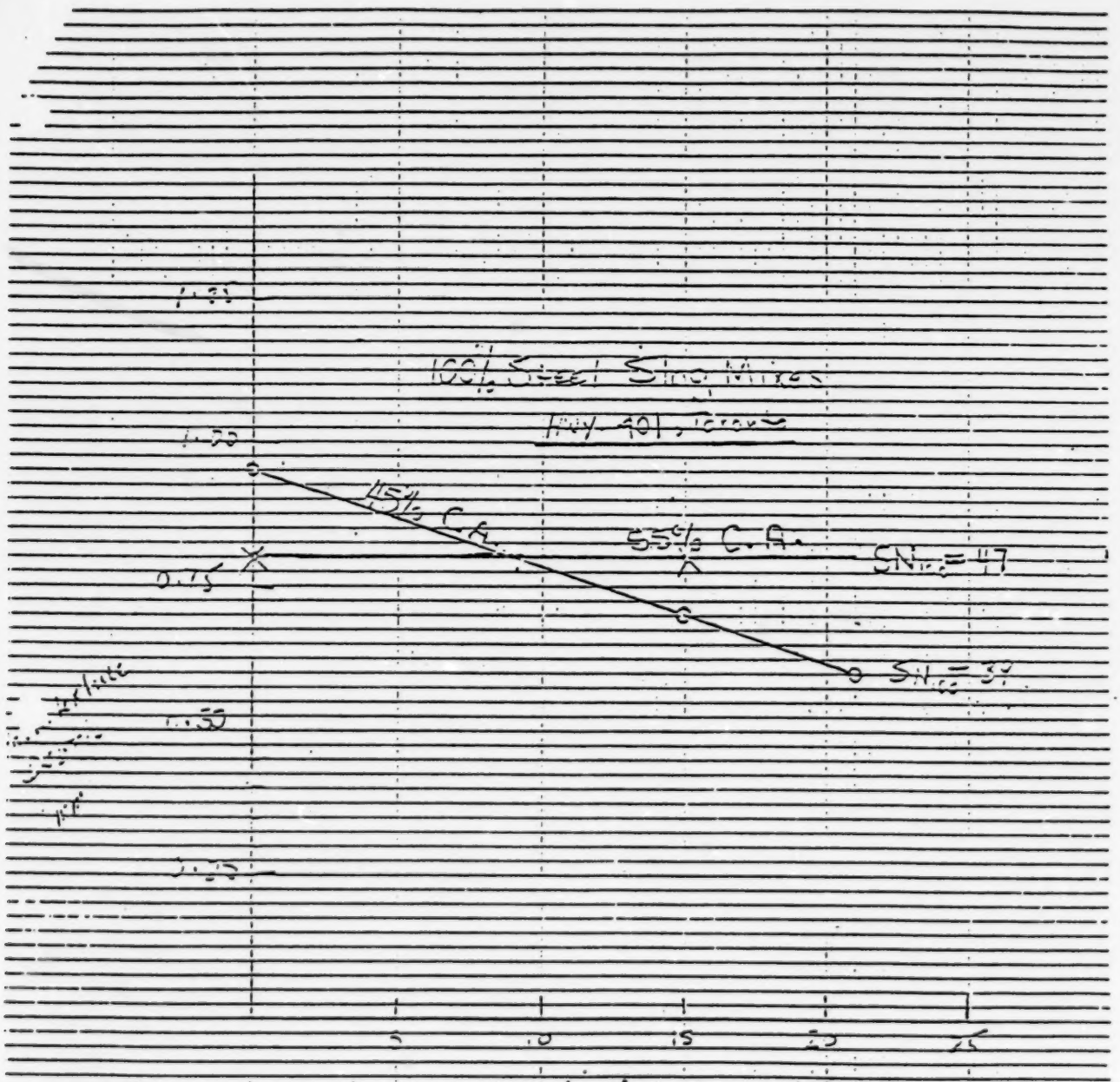


Fig. 4 Allowable Depth vs. Pavement Age for 100% Steel Strip Test Mixes.

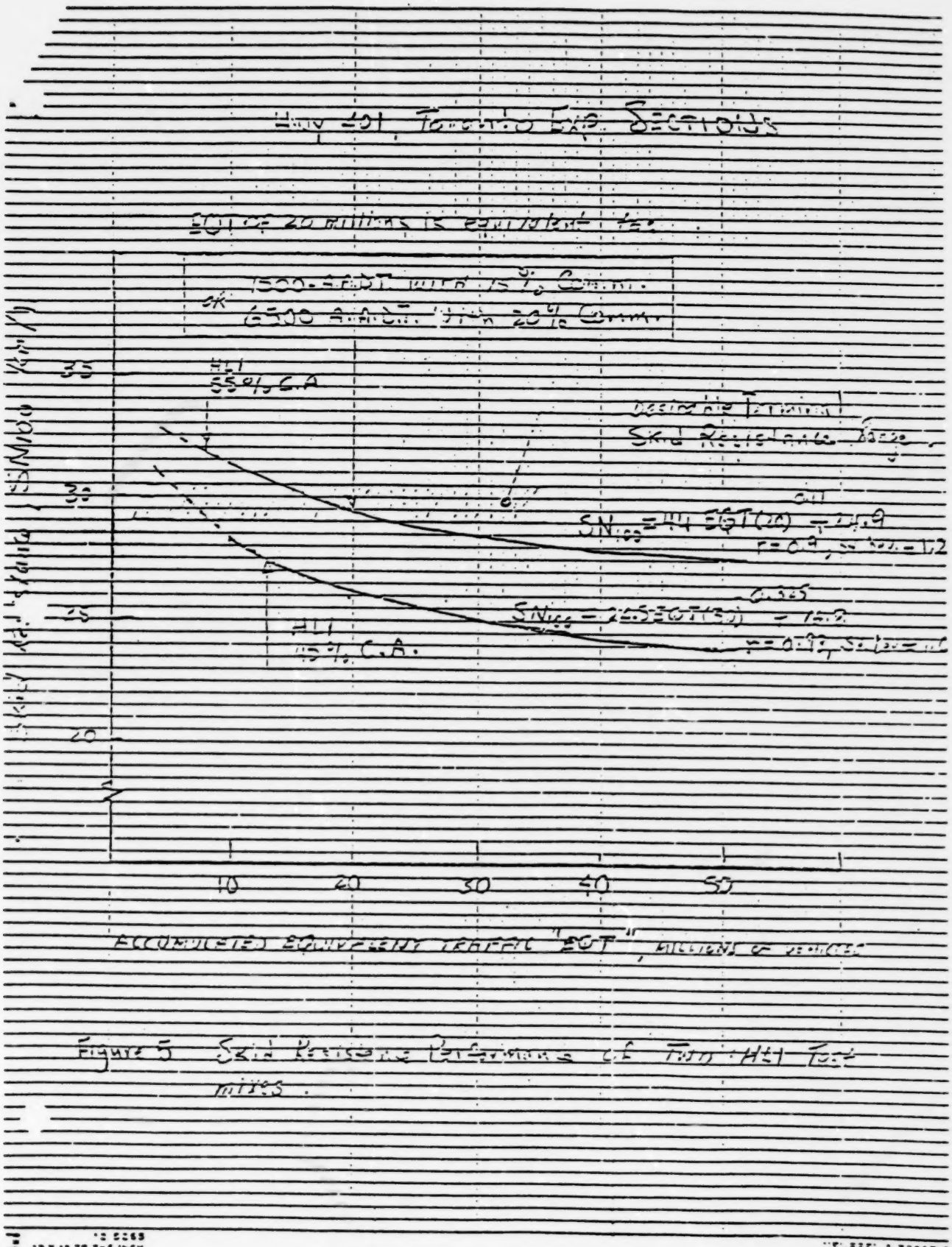


Figure 5 Skid Resistance Variance of Two Hot Mixes.

APPENDIX D

STUDY TEST DATA

PAGE LAYOUT FOR CONTRACT DATA

PAGE 67

For Cont. No. 77-50 to 81-61
-District
-Hwy. No.
-Tonnes
-CA Type
-FA Type
-Tender %

PAGE 68

For Cont. No. 77-50 to 81-61
-Design Parameters
A.C. (D)
C.A. (D)
Voids (D)
Flow (D)
Stab. (D)
VMA (D)
%Pass (D)
-Mobile Lab. Values
No. Of Lab. Checks n(M)
A.C. Mean (x)
A.C. Std Dev (σ)
C.A. Mean (x)
C.A. Std Dev (σ)
Voids Mean (x)
Voids Std Dev (σ)
Flow Mean (x)
Flow Std Dev (σ)

PAGE 69

For Cont. No. 77-50 to 81-61
-MobileLab.Values(cont.)
Stab. Mean (x)
Stab. Std Dev (σ)
VMA Mean (x)
VMA Std Dev (σ)
%Pass Mean (x)
%Pass Std Dev (σ)
BRD Mean (x)
BRD Std Dev (σ)
MRD Mean (x)
MRD Std Dev (σ)
-Field Lab. Values
No. of Field Checks n(F)
A.C. Mean (x)
A.C. Std Dev (σ)
C.A. Mean (x)
C.A. Std Dev (σ)
%Pass Mean (x)
%Pass Std Dev (σ)

PAGE 70

For Cont. No. 81-65 to 83-76
-District
-Hwy. No.
-Location
-Tonnes
-CA Type
-FA Type
-Tender %

PAGE 71

For Cont. No. 81-65 to 83-76
-Design Parameters
A.C. (D)
C.A. (D)
voids (D)
Flow (D)
Stab. (D)
VMA (D)
%Pass (D)
-Mobile Lab. Values
No.of Lab.Checks
A.C. Mean (x)
A.C. Std Dev(σ)
C.A. Mean (x)
C.A. Std Dev (σ)
Voids Mean (x)
voics Std Dev (σ)
Flow Mean (x)
Flow Std Dev (σ)

PAGE 72

For Cont. No. 81-65 to 83-76
-Mobile Lab. Values(cont.)
Stab. Mean (x)
Stab. Std Dev (σ)
VMA Mean (x)
VMA Std Dev (σ)
%Pass Mean (x)
%Pass Std Dev (σ)
BRD Mean (x)
BRD Std Dev (σ)
MRD Mean (x)
MRD Std Dev (σ)
-Field Lab. Values
No. of Field Checks
A.C. Mean (x)
A.C. Std Dev (σ)
C.A. Mean (x)
C.A. Std Dev (σ)
%Pass Mean (x)
%Pass Std Dev (σ)

DFC TEST RESULTS

(x) STA	D. (σ)	(x) VH	A (σ)	(x) %P	ASS(σ)	(x) D	ND (σ)	(x) M	ND (σ)	n(F)	(x) A.	C. (σ)	(x) C.	A. (D)	(x) % P	ASS (σ)
15604.4	447.1	14.40	.81	8.12	.53	2.877	.016	2.938	.012	21.	4.37	.19	43.80	3.46	6.44	1.11
16253.8	497.9	14.70	.80	8.99	.88	2.751	.021	2.831	.010	8.	4.18	.24	41.80	5.38	7.88	.74
17735.1	310.3	15.90	.28	9.10	.29	2.767	.009	2.873	.004	6.	4.73	.18	46.30	4.55	8.15	.50
18541.5	210.9	19.17	.64	5.21	.34	3.022	.018	3.133	.033	6.	5.67	.23	43.57	3.04	4.42	.39
15107.9	1076.7	17.79	.93	4.27	.61	3.020	.027	3.107	.032	18.	5.84	.35	45.29	4.91	3.97	.54
19975.6	453.0	18.43	.80	4.54	.78	3.034	.014	3.204	.015	68.	4.79	.32	46.47	4.08		
9078.8	181.0	18.95	1.65	3.50	1.00	2.571	.044	2.779	.025	1.	4.60		52.00		6.50	
20535.2	272.7	19.01	.99	4.40	.26	2.994	.015	3.087	.017	19.	5.51	.34	47.90	4.67	4.80	.30
17457.9	510.6	15.30	1.16	5.07	.19	2.746	.033	2.839	.003							
20223.4	267.1	19.83	.60	4.18	.42	3.022	.019	3.102	.018							
23718.4	509.4	18.07	.57	4.25	1.21	2.868	.010	2.952	.019							
20213.2	211.8	19.28	.84	4.12	.37	3.027	.015	3.087	.012	28.	5.49	.23	45.26	5.04	4.91	.67
15434.9	511.2	19.65	.97	4.83	.78	3.047	.036	3.135	.021	3.	5.67	.21	50.60	2.55	4.90	.16
16049.2		17.10		4.13	.23	2.873		2.988		9.	5.10	.13	51.70	4.96		
19731.4	346.2	19.40	.89	3.60	.88	3.005	.038	3.080	.049	22.	5.57	.19	49.90	4.67		
20175.4	183.1	19.68	1.05	3.85	.52	2.995	.025	3.087	.015	8.	5.85	.33	48.53	6.17		
15551.0		16.60		7.30												
20608.8	181.3	20.47	.79	5.20	.42	2.997	.056	3.149	.064	2.	5.49	.07	44.20	.20	2.25	.45
16491.8	237.5	15.30	.83	7.54	1.37	2.837	.110	2.835	.021	4.	4.92	.12	44.30	1.55	7.13	1.68
13719.2	726.6	15.60	.90	7.47	.84	2.772	.038	2.841	.037	14.	4.36	.18	45.80	3.00	7.24	.52
18804.4	526.4	19.64	1.01	4.32	.68	3.017	.031	3.104	.036	21.	5.90	.33	49.34	5.25	4.65	.68
12755.3	321.8	16.12	1.37	5.83	1.27	2.766	.041	2.832	.015	21.	4.82	.24	45.02	3.27	6.80	1.67
18535.7	615.0	19.00	1.46	4.13	.71	3.029	.054	3.193	.039	15.	5.36	.14	41.30	3.41	3.60	.58
15684.0	221.8	17.66	.71	4.32	.55	3.069	.024	3.136	.018	7.	5.44	.21	46.17	2.42	4.41	.58
18953.5	217.8	14.97	1.86	8.21	.85	2.711	.040	2.809	.014	3.	4.86	.28	40.20	3.30	7.73	1.06
17167.0	618.7	18.10	1.08	3.72	.41	3.025	.039	3.123	.025	13.	5.51	.27	45.72	3.49	3.82	.47
16237.7	582.6	19.78	1.02	3.33	2.29	3.017	.065	3.196	.020	13.	5.23	.07	41.15	4.48		
16838.7	396.0	16.58	.78	8.33	1.13	2.778	.019	2.924	.036	2.	3.98	.03	45.50	.50		
18616.7	305.9	14.82	.57	7.47	1.38	2.777	.024	2.832	.033	4.	4.41	.22	41.98	1.67	7.63	1.08
17723.5	751.4	19.46	1.12	4.20	1.37	2.965	.029	3.145	.025	12.	5.13	.19	39.48	5.70		
16387.3	186.0	15.95	.85	6.20	1.30	2.732	.037	2.863	.011	4.	4.62	.14	44.50	1.24	6.25	2.58
11955.9	606.3	14.78	.86	8.06	.92	2.728	.015	2.766	.010	17.	4.80	.12	44.64	1.75	7.25	.69
19822.2	668.0	17.50	.35	3.95	.51	2.983	.006	3.071	.029							
24898.9	550.1	17.65	1.74	4.18	.48	2.851	.022	2.983	.024							
18928.5	211.3	14.03	.53	5.86	.82	2.448	.014	2.496	.011	10.	4.95	.24	44.71	3.80	5.71	.43
16995.3	655.2	18.70	2.12	3.52	.46	3.004	.023	3.114	.039	3.	5.96	.20	44.07	1.84	3.13	.09
18720.5	798.1	15.05	.70	3.60	.59	2.772	.058	2.841	.053	4.	5.33	.13	47.70	1.11	3.10	.54
17933.0	1041.0	17.95	1.95	4.00	.96	2.748	.204	2.894	.198	3.	4.86	.11	47.60	4.10	3.56	1.07
13926.5	545.1	18.27	1.68	4.11	.65	3.048	.057	3.161	.018	7.	5.54	.33	48.50	3.16		
12505.3	613.5	14.63	.18	7.00	.56	2.718	.015	2.772	.005	5.	5.11	.43	47.60	2.47	6.38	1.47
16769.8	457.0	15.90	.10	5.85	.85	2.907	.020	2.948	.018	2.	6.45	.25	36.95	1.95	4.80	1.50
23159.3	4409.1	17.50	.40	3.85	.15	2.858	.038	2.935	.054	12.	5.56	.27	44.10	5.52	3.70	.50
17035.1	1442.0	18.30	.69	3.76	.89	2.909	.021	2.984	.014	1.	5.70		47.50		4.30	
19154.0		21.20		3.60		2.971		3.124		1.	6.25		47.90		4.20	

DFC TEST RESULTS

(x) STA	B. (σ)	(x) VH	A (σ)	(x) %P	ASS(σ)	(x) B	MD (σ)	(x) M	MD (σ)	n(F)	(x) A.	C. (σ)	(x) C.	A. (D)	(x) % P	ASS (σ)
11121.0	271.2	15.80	1.76	5.49	1.98	2.688	.047	2.783	.030	6.	4.97	.24	42.40	5.80	5.93	.52
11821.6	158.2	14.00	.42	7.20	.49	2.732	.012	2.773	.025	2.	4.59	.18	51.50	.20	7.00	.30
14209.0	743.9	16.20	.86	6.35	1.28	2.706	.013	2.786	.021	8.	5.17	.15	41.80	3.80	6.11	1.19
14899.0	1469.1	15.94	.58	7.07	.40	2.680	.027	2.763	.021	7.	4.70	.11	46.59	3.60	6.49	.36
15178.2	1317.6	18.45	1.01	3.36	.41	2.943	.024	3.091	.018	40.	5.26	.26	44.80	1.94	3.30	.38
19055.1	2296.9	19.67	.42	4.39	.97	2.872	.020	2.991	.036	8.	5.82	.53	46.20	1.74	4.35	1.34
17886.3	597.1	19.65	.95	3.28	.38	3.068	.026	3.172	.017	1.	5.78		48.80		2.90	
14061.6	1623.3	17.00	.31	4.71	.41	2.828	.028	2.875	.028	26.	5.61	.32	43.17	3.73	4.84	.87
				4.28	.43					4.	5.25	.38	51.60	9.86	4.28	.43
16792.0	2739.8	16.80	4.26	7.04	1.21	2.709	.014	2.773	.005	6.	4.95	.22	44.40	3.13	7.50	.77
19015.5	426.5	16.60	.40	5.37	.68	2.867	.007	2.978	.016	9.	5.20	.32	44.80	2.84	5.12	1.11
13029.0	2405.6	16.10	2.01	5.85	.79	2.628	.031	2.754	.023	15.	4.57	.17	57.25	2.52	5.62	1.22
16169.0	2178.1	12.30	.71	3.87	.37	2.941	.023	3.028	.066	4.	5.32	.12	50.50	1.73	3.85	.57
16230.0	1554.1	11.77	2.70	4.53	1.23	3.000	.022	3.089	.048	3.	5.49	.33	48.73	3.39	4.33	.74
15936.0	696.0	10.55	.45	2.63	.31	2.852	.021	2.997	.026	2.	5.57	.31	51.66	2.35	2.60	.40
18480.0	4719.0	18.80	.70	2.83	1.64	2.962	.012	3.086	.020	2.	5.68	.08	48.75	.75	3.90	.90
20107.0	1870.0	18.45	.95	4.00	.30	3.085	.023	3.169	.007							
14203.0	1046.2	20.30	.58	4.50	.15	2.962	.010	3.080	.006	6.	5.37	.14	50.20	2.71	5.42	.56
15597.7	1700.1	15.90	.99	7.27	.78	2.608	.022	2.711	.008	9.	4.70	.14	54.35	4.17	6.62	.57
10636.4	1413.8	16.90	1.22	6.70	1.10	2.601	.038	2.751	.021	4.	4.68	.17	45.14	2.78	7.02	.89
21230.0	2893.6			3.72	.58	2.922	.056	3.021	.034	4.	5.58	.16	53.20	5.35	4.18	.58
13247.0	2013.7	18.50	.95	3.78	.73	2.869	.030	3.010	.024	14.	5.23	.31	58.50	6.01	4.07	.88
15306.0	704.4	15.58	.50	6.33	.96	2.675	.027	2.811	.012	6.	4.34	.06	55.52	2.73	5.93	.49
20586.3	1021.9	8.07	1.73	4.60	.70	2.523	.055	2.654	.035	4.	6.48	.19	38.77	1.99	5.47	.80
19225.2	1017.2	14.72	2.10	3.22	.81	2.663	.072	2.799	.089	1.	5.19		47.70		6.10	
12914.0		11.60		8.10		2.564		2.678		2.	4.90	.40	44.60	1.60	6.70	.30
15077.2	1891.4	16.10	1.14	8.07	1.18	2.734	.055	2.807	.023	5.	4.85	.21	45.80	2.51	6.16	1.23
12955.0	1594.3	16.78	.97	5.52	.90	2.647	.023	2.783	.021	4.	4.62	.11	53.60	2.27	5.75	1.06
19213.0	1645.2	10.80	.78	4.75	.77	2.952	.041	3.060	.026	15.	5.53	.18	46.10	2.04	4.35	.59
21024.3	2307.2	16.75	1.07	4.75	.53	2.916	.033	3.090	.029	9.	5.22	.36	49.76	1.94	4.77	.56
19004.0	3144.1	16.62	1.50	4.23	.49	2.956	.024	3.088	.037	6.	4.87	.06	52.70	3.23	4.92	.48
22268.0	2186.9			3.84	.58	2.928	.018	3.014	.028	5.	5.08	.15	47.50	2.90	3.92	.61
15556.5	4355.7			4.24	.66	2.877	.045	3.024	.051	5.	5.48	.18	50.40	1.71	3.60	.90
22738.9	2634.9	10.40	1.37	4.24	.53	2.457	.040	2.701	.025	9.	6.67	.20	44.84	3.52	4.10	.58
17954.0	399.5	13.35	.38	3.48	.64	2.425	.015	2.481	.010	7.	4.72	.28	52.31	2.98	4.47	.89
19952.3	1082.4	16.47	.72	3.50	.48	2.892	.042	3.077	.050	4.	5.33	.37	54.23	8.35	3.50	.10
23098.0		12.10		4.80	.80	2.778		2.981		2.	5.36	.25	41.70	1.60	5.30	.80
14315.0	1168.0	13.15	1.75	8.00	.00	2.605	.007	2.764	.005	4.	4.53	.28	40.42	4.92	6.72	.77
21611.4	2566.3			4.14	.25	2.926	.020	3.028	.023	3.	5.36	.15	53.10	2.50	4.60	.17
				4.48	.33					14.	5.27	.27	46.60	2.39	5.33	.60
21447.0	3145.3	10.90	.53	3.92	.41	2.818	.026	2.980	.018	3.	5.36	.14	41.30	1.64	3.87	.31
15479.0				5.60		2.594		2.766		4.	4.33	.17	45.78	2.69	5.53	.74
18665.2	1347.7	11.10	.30	4.39	.39	2.963	.017	3.076	.025	19.	5.54	.21	50.17	3.70	4.06	.54
25441.0				6.20		2.836		2.927		3.	4.43	.75	42.00	2.70	6.90	.67

DFC TEST RESULTS

Cont. No.	Dist.	Hwy #	LOCATION	Tonnes	CA TYPE	FA TYPE	TENDER %
77-50	9	417	Hurdman Bridge East to St. Laurent Blvd.	7,620	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
78-02	8	2	Highway 2 at Sydenham Road	3,447	3m Havelock	Arnbro Harmora Unw. Scr.	45.00
78-102	7	7	Highway 30 Easterly to Havelock East Limits	2,948	3m Havlock	Arnbro Harmora Unw. Scr.	45.00
78-111	6	427	Rexdale and Indian Line	6,400	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
78-53	6	7	Brampton to Georgetown	14,610	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
78-55	1	401	Tilbury to Bloomfield Road	27,215	Levy Steel Slag	Levy Steel Slag	45.00
78-73	6	401	Bathurst to Steeles	544	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
78-93	4	2	Highway 53 Interchange	17,236	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-100	8	400	Rutherford Road Interchange	1,996	3m Havelock	Arnbro Harmora Unw. Scr.	45.00
79-101 A	4	403	Q.E.W. West to Highway 6	285	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
79-101 B	4	403	Q.E.W. West to Highway 6	285	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
79-102	4	2	Alberton West to Highway 54	16,329	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-113	4	Q.E.W.	Trafalgar Road Interchange	3,855	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-24	6	7	.2 m East of Hwy. 27 to .8 m East of Airport Road	806	Arnbro Harmora	Stelco Steel Slag Unw. Scr.	45.00
79-25	6	401	Derry Road to West of Trafalgar Road	1,361	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-31	4	403	Oakville Link-Hwy. 5 & v/pass, Burnhamthorpe Road	504	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-542	6	7	West of Kipling	48	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
79-543	4	451	East Main Tunnel Welland	1,906	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-69	6	401	E/B Collector to Weston Road	544	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
79-74	6	404	7th Avenue Interchange	24,040	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
79-80	4	Q.E.W.	Ford Drive Interchange	12,700	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
79-84	6	401	Neilson Road Interchange	2,903	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-04	1	E.C. Rowe	E.C. Rowe Highway	6,032	Levy Steel Slag	Levy Steel Slag	45.00
80-20	4	403	Highway 5 to Winston Churchill Road	2,630	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
80-22	6	7	Jane Street to CNR Overpass	2,630	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-30	4	6	Milgrove to Freelton	19,050	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
80-33	1	E.C. Rowe	E.C. Rowe Highway	4,990	Levy Steel Slag	Levy Steel Slag	45.00
80-39	2	126	Highbury Ave Interchange	1,315	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-42	6	Q.E.W.	Wickman Road Interchange	227	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-43	1	E.C. Rowe	E.C. Rowe Highway	4,990	Levy Steel Slag	Levy Steel Slag	45.00
80-50	6	427	427 and 401 S.E. Ramp	998	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-55	7	401	Oshawa to East of Waverly Road	24,494	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-59	8	401	Keele to Highway 400	100	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
80-66	4	Q.E.W.	Burlington Street to Highway 20	284	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
80-67	9	17	Blair Road to Montreal Road	6,214	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
80-71	6	403	Winston Churchill to Credit River	9,525	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
81-107	6	401	From Bathurst Street to Islington Avenue W.B. Core	619	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
81-108	6	401	From Bathurst Street to Islington Avenue E.B. Core	534	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
81-24	4	401	?????	523	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
81-38	6	401	Younge Street Interchange Including 2 Structures	1,607	Arnbro Harmora	Arnbro Harmora Unw. Scr.	45.00
81-41	4	408	Beaverdams Road and Highway 408	44	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
81-48	8	427	From Highway 401 North to Fasken Drive	580	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
81-56	4	Q.E.W.	St. Catharines Garden City Skyway	6,247	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
81-57	4	Q.E.W.	Ice Creek Interchange	230	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00

OFC TEST RESULTS

A.C. (D)	C.A. (D)	VOIDS(D)	FLOW(D)	STAB. (D)	VMA(D)	%PASS(D)	n(M)	(x) A.	C. (σ)		(x) C.	A. (σ)		(x)VOI	DS(σ)		(x) FL	OW (σ)	
4.30	45.00	2.00	20.20	12810.9	12.90		19	4.31	.21		43.50	3.41		2.07	.65		12.36	.96	
4.00	45.00	1.50	18.00	13389.1	12.70	7.40	9	4.34	.19		40.60	2.02		2.84	.82		12.30	1.72	
4.30	45.00	2.00	23.00	17348.1	13.60	8.40	3	4.52	.02		46.30	4.97		3.37	.31		20.80	2.21	
5.60	45.00	1.60	18.40	19305.3	14.00	4.70	7	5.38	.34		43.17	3.68		3.51	.76		16.16	.95	
5.60	45.00	2.80	18.20	18237.7	20.00	5.30	15	5.46	.32		45.81	3.06		1.45	1.28		15.63	1.09	
4.70	45.00	2.80	17.80	22107.7	17.80	4.00	77	4.71	.26		44.54	4.23		4.15	.84		18.09	1.41	
4.40	45.00	1.30	21.50	15457.6	12.80	6.70	2	4.49	.43		50.50	.20		9.40	1.20		15.45	2.45	
5.30	45.00	2.00	15.80	18860.5	18.20	3.60	15	5.60	.22		47.83	5.56		2.15	1.19		17.48	.62	
4.30	45.00	2.00	23.00	17348.1	12.50	8.40	3	4.41	.26		49.90	1.03		3.27	1.09		14.52	.74	
5.70	45.00	3.70	19.50	21262.5	19.80	3.20	13	5.70	.22		52.24	1.91		2.61	.86		16.56	1.95	
6.00	45.00	2.30	18.00	23353.2	19.30	4.80	7	6.01	.33		44.71	1.38		.84	.49		21.35	1.35	
5.60	45.00	1.30	22.30	18415.6	17.50	5.00	8	5.73	.28		46.80	4.28		1.94	.38		19.56	.72	
5.70	45.00	3.70	19.50	21262.5	19.80	3.20	11	5.58	.24		44.66	1.85		2.66	.99		16.69	.88	
5.10	50.00	3.80	13.70	14679.1	18.30	4.60	1	4.79	.27		52.40	6.47		3.90			13.10		
5.60	45.00	3.00	15.10	18839.1	18.00	4.90	26	5.69	.25		50.10	4.44		2.33	1.19		17.89	1.69	
5.70	45.00	3.70	19.50	21262.5	19.80	3.20	7	5.65	.38		50.16	4.99		2.99	1.10		18.14	.86	
4.30	45.00	2.00	23.90	17348.1	13.60	8.40	1	4.62			41.20			3.80			15.00		
5.30	45.00	2.00	15.80	18860.5	18.20	3.60	3	5.22	.09		40.87	.90		4.83	.34		17.23	1.02	
4.40	45.00	2.00	18.50	11520.9	13.50	8.20	4	4.67	.21		43.30	2.60		2.15	.93		20.80	4.25	
4.20	45.00	2.20	18.00	16569.6	13.80	9.30	28	4.75	.36		44.06	3.44		2.44	1.03		15.60	1.67	
5.70	45.00	3.70	19.50	21262.5	19.80	3.20	22	5.61	.39		48.51	6.32		2.76	1.23		18.34	1.95	
4.50	45.00	1.30	21.40	14123.1	13.80		20	4.96	.23		43.20	3.47		2.45	1.68		15.00	2.22	
5.20	40.00	2.70	18.00	17970.8	18.00	5.13	15	5.33	.19		38.80	3.69		2.48	1.41		16.50	1.07	
5.60	45.00	1.60	19.40	19305.3	14.00	4.70	18	5.63	.21		47.83	2.31		.50	.53		16.47	1.23	
4.50	45.00	1.30	21.50	15457.6	12.80	6.70	5	4.64	.22		39.24	1.91		3.43	1.89		18.53	1.33	
5.60	45.00	1.60	19.40	19305.3	14.00	4.70	38	5.43	.24		47.18	4.19		1.63	1.34		16.74	1.26	
5.20	40.00	2.70	18.50	17970.8	18.00	5.20	14	5.54	.17		39.35	4.12		4.21	1.65		16.65	.90	
4.20	45.00	2.80	17.30	16102.6	14.50	9.80	4	4.17	.22		42.10	2.93		5.00	.70		14.83	.58	
4.20	45.00	2.20	21.40	18104.3	13.50	9.00	4	4.65	.08		42.07	2.58		1.93	.49		18.30	1.82	
5.20	40.00	2.70	18.50	17970.8	18.00	5.20	26	5.10	.25		40.36	8.04		4.39	1.20		15.90	1.08	
4.20	45.00	2.20	21.40	18104.3	13.50	9.30	2	4.27	.04		44.60	.20		4.60	.90		14.55	1.15	
4.50	45.00	1.30	21.50	15457.6	12.80	6.70	8	5.01	.20		40.82	3.18		.89	.58		15.66	2.61	
5.60	45.00	1.60	19.40	19305.3	14.00	4.70	4	5.48	.22		42.83	1.78		1.40	1.06		15.73	.58	
5.70	45.00	3.80	18.20	25132.5	19.20	5.60	8	5.36	.33		43.85	3.11		2.38	1.00		20.68	.84	
4.80	45.00	2.10	14.40	11120.6	11.80	6.90	7	4.91	.18		44.18	4.23		1.91	.45		14.54	1.75	
5.60	45.00	1.60	19.40	19305.3	14.00	4.70	7	5.43	.25		45.11	2.12		2.67	1.75		15.59	1.73	
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	4	5.32	.12		47.60	1.57		.85	.68		16.75	1.56	
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	3	5.16	.46		48.90	3.34		3.95	.85		13.70	3.20	
5.60	45.00						10	5.33	.16		50.44	1.96		2.08	1.96		16.61	2.01	
4.50	45.00	1.30	21.50	15457.6	12.80	6.70	4	4.78	.18		48.70	.64		1.65	.59		18.30	2.36	
6.20	55.00						2	5.89	.21		44.20	4.00		.10	.10		21.40	.15	
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	2	5.36	.42		45.60	2.40		2.40	.50		19.40	1.74	
5.90	45.00	2.20	27.40	12500.0		7.60	12	5.73	.18		44.60	3.11		1.68	.71		19.83	1.92	
5.60	45.00	1.60	18.40	19305.3	14.00	4.70	1	5.64			47.70			4.90			18.10		

DFC TEST RESULTS

Cont. No.	Dist.	Hwy #	LOCATION	Tonnes	CA TYPE	FA TYPE	TENDER %
81-59	6	400	Highway 400 and Highway 401 Interchange Ramps	877	Armbro Harmora	Armbro Harmora Unw. Scr.	45.00
81-60	6	400	Highway 400 and Highway 401 Interchange Ramps	879	Armbro Harmora	Armbro Harmora Unw. Scr.	45.00
81-61	6	7	7 North and Kennedy Rd. and Heart Lake Rd.	2,631	Armbro Harmora	Armbro Harmora Unw. Scr.	45.00
81-65	6	404	From Gormbey Road to Vandorf Road	9,950	Armbro Harmora	Armbro Harmora Unw. Scr.	45.00
81-67	6	401	Trafalgar Road to Highway 25 and James Snow Int.	30,500	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
81-72 A	4	O.E.W.	Fifth Street to Hartindale Road	5,100	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
81-72 B	4	O.E.W.	Fifth Street to Hartindale Road	5,100	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
81-86	4	O.E.W.	Tee Creek to Gilmore Road	33,898	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
81-90	6	10	Matheson Blvd. to Traders Blvd.	2,600	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
81-93	8	27	Old 27 and Kipling Avenue Overpass	1,300	3m Havelock	Armbro Harmora Unw. Scr.	55.00
81-96	8	Black Creek	South of Eglinton Avenue	2,386	Dofasco Basic Oxygen Furnace Slag	Armbro Harmora Unw. Scr.	45.00
82-03	7	401	Waverly Road to 35/115 Interchange	23,482	3m Havlock	Armbro Harmora Unw. Scr.	55.00
82-101	6	427	Various Bridge Decks	824	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
82-102	6	427	Various Bridge Decks	942	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
82-112	6	401	Jane to Bathurst	590	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	55.00
82-113	6	401	Jane to Islington W/B Collectors	356	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
82-26	4	2	Ancaster Bridge	536	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
82-34	4	25	North of Steeles	2,090	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
82-41 A	6	401	Whites Road	5,757	3m Havelock	Armbro Harmora Unw. Scr.	55.00
82-41 B	6	401	Whites Road	5,757	3m Havelock	Armbro Harmora Unw. Scr.	55.00
82-59 A	4	24	Brantford	9,255	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	55.00
82-59 B	4	24	Brantford	9,255	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	55.00
82-63	6	7	[illegible] m Highway 404 to Woodbine	4,547	Minnesota Mining Traprock	Armbro Harmora Unw. Scr.	55.00
82-72 A	6	401	Thickson Road	906	Blast Furnace Slag	Dofasco Steel Slag Unw. Scr.	55.00
82-72 B	6	401	Thickson Road	906	Lasco Steel Slag	Lasco Steel Slag Unw. Scr.	55.00
82-72 C	6	401	Thickson Road	906	3m Havelock	Armbro Harmora Unw. Scr.	55.00
82-81 A	7	401	W.B. 401 Bowmanville to Oshawa	14,610	Armbro Harmora	Armbro Harmora Unw. Scr.	55.00
82-81 B	7	401	W.B. 401 Bowmanville to Oshawa	14,610	3m Havlock	Armbro Harmora Unw. Scr.	55.00
82-85	4	O.E.W.	Highway #2 Interchange	7,403	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	45.00
82-87 A	6	27	Regional Road 49 and Humber River	5,030	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
82-87 B	6	27	Regional Road 49 and Humber River	5,030	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
83-01	4	O.E.W	From Garden City Skyway Easterly 2.2 km	4,290	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
83-11	4	O.E.W.	QEW : Fairview to Burlington	4,290	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	55.00
83-20	6	7	Leslie Street to 401	5,460	Blast Furnace Slag	Dofasco Steel Slag Unw. Scr.	55.00
83-22	9	417	Maitland Ave to Island Park Drive	2,794	Armbro O (Ottawa)	Armbro O (Ottawa)	55.00
83-27	6	427	North of Rexdale	2,045	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
83-34	4	O.E.W.	??	228	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	55.00
83-406	6	401	Truck Inspection Station	1,897	3m Havelock	Armbro Harmora Unw. Scr.	55.00
83-41	4	O.E.W.	Burlington Street Interchange	3,079	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
83-43 A	4	O.E.W.	Tee Creek to Lundys Lane	996	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
83-43 B	4	O.E.W.	Tee Creek to Lundys Lane	996	Dofasco Steel Slag	Dofasco Steel Slag Unw. Scr.	45.00
83-68	6	401	Dixie to Matheson	15,438	3m Havelock	Armbro Harmora Unw. Scr.	55.00
83-71	6	401	Dixie Road to Renforth	23,691	Stelco Steel Slag	Stelco Steel Slag Unw. Scr.	55.00
83-76	4	58	Pine Street Interchange	245	3m Havelock	Armbro Harmora Unw. Scr.	45.00

OFC TEST RESULTS

A.C. (D)	C.A. (D)	VOIDS(D)	FLOW(D)	STAB. (D)	VMA(D)	MPASS(D)	n(H)	(x) A.	C. (σ)		(x) C.	A. (σ)		(x)VOI	DS(σ)		(x) FI	OW (σ)
4.50	45.00	1.30	21.50	15457.6	12.80	6.70	14	4.83	.20		47.00	4.40		3.00	2.31		14.00	2.42
4.50	45.00	1.30	21.50	15457.6	12.80	6.70	5	4.83	.28		50.50	1.94		.80	.70		15.50	.66
4.70	45.00	1.40	20.80	14857.1	13.60	8.50	4	4.87	.17		38.20	3.51		2.83	.85		13.90	1.42
4.70	45.00	2.20	22.10	16000.0	14.50	7.20	11	4.88	.15		46.11	3.75		2.82	.72		15.80	1.91
5.50	45.00	1.30	18.30	22900.0	11.10	2.00	35	5.46	.31		44.69	2.58		2.35	.86		18.12	1.79
5.80	45.00	1.60	19.40	19305.3	14.00	4.70	7	5.58	.28		44.40	1.87		3.96	.94		18.70	1.55
5.60	45.00	1.60	19.40	19305.3	14.00	4.70	4	5.34	.12		51.28	3.49		3.43	1.20		17.38	1.34
5.90	45.00	2.20	27.40	12500.0			15	5.87	.17		42.62	2.83		.41	.49		19.57	1.32
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	2	4.85	.21		46.10	1.10						
4.70	45.00	1.90	21.30	13500.0	12.50	6.90	5	4.73	.25		43.32	4.36		2.33	.67		17.68	4.02
5.00	45.00	1.10	22.70	18450.0	13.60	8.20	3	5.07	.08		48.30	4.68		2.65	.35		18.15	.65
4.60	55.00	2.00	18.70	13600.0	13.50	7.50	33	4.49	.31		55.90	3.32		4.57	1.38		15.80	2.48
5.50	45.00	1.30	18.30	22900.0	11.10	2.00	3	5.52	.49		51.30	6.26		.97	.69		18.37	2.97
5.50	45.00	1.30	18.30	22900.0	11.10	2.00	3	5.27	.13		50.23	1.24		.60	.85		22.03	2.17
5.60	45.00	2.40	17.00	23500.0	10.10	3.40	2	5.85	.21		50.87	3.13		2.75	1.55		17.00	1.50
5.50	45.00	1.30	18.30	22900.0	11.10	2.00	2	5.54	.26		53.40	6.75		1.65	.25		17.75	.75
5.90	45.00	2.20	27.40	12500.0			2	5.49	.18		49.65	2.85		.90	.90		19.05	.85
5.30	55.00	1.20	24.00	18800.0	12.80	5.20	4	5.56	.26		50.80	.75		2.55	.98		17.80	1.18
4.60	45.00	2.00	18.70	13600.0	13.70	8.90	7	4.59	.34		43.87	2.54		3.79	.93		17.61	1.13
4.50	55.00	2.00	18.70	13600.0	13.50	7.50	6	4.40	.26		54.52	3.40		5.47	1.28		15.28	2.58
5.60	55.00	2.50	18.50	18600.0	12.40	3.30	6	5.34	.13		56.10	3.20		3.28	1.44		17.70	1.61
5.60	57.60	2.50	18.50	18600.0	12.40	3.30	11	5.30	.18		58.30	4.72		3.36	1.33		20.50	1.11
4.20	55.00	2.50	18.50	14700.0	12.70	6.60	6	4.34	.09		53.62	2.18		4.86	.88		14.26	1.77
7.00	40.00	1.70	16.90	25600.0	12.10	3.60	4	6.58	.30		38.14	3.51		1.10	1.28		17.13	4.65
5.70	46.50	2.50	18.50	26300.0	10.80	4.80	5	5.54	.52		44.32	5.53		2.36	.97		21.86	2.62
4.60	45.00	2.00	18.70	13600.0	13.70	8.90	2	4.71	.11		46.70	2.43		4.90			15.70	
4.50	45.00	1.30	21.50	15457.7	12.80	6.70	9	4.93	.28		42.40	1.77		2.68	1.99		16.24	1.17
4.60	55.00	2.00	18.70	13600.0	13.50	7.50	5	4.63	.20		53.20	4.26		4.56	1.23		15.44	4.02
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	10	5.54	.26		44.20	1.76		1.83	1.06		18.56	3.16
4.80	57.10	2.50	18.80	22400.0	13.70	4.40	11	4.76	.26		52.03	2.38		3.19	.84		19.03	3.56
4.80	55.00	2.50	18.90	22400.0	13.70	4.40	4	5.01	.14		52.47	1.93		2.55	1.31		21.65	.50
5.60	45.00	1.20	24.00	18800.0	12.80	5.20	7	5.21	.17		45.80	1.65		1.90	1.14		16.70	1.18
5.60	55.00	2.30	16.60	25100.0	11.30	2.90	4	5.39	.21		51.60	2.69		4.85	1.21		16.90	1.95
6.80	46.40	2.50	18.80	24800.0	12.90	3.70	9	6.46	.27		45.06	4.10		3.23	1.14		15.77	1.03
4.60	55.00	2.10	14.90	18000.0	14.50	4.30	4	5.26	.19		53.88	2.13		2.28	.96		14.73	1.64
5.50	47.90	1.30	18.50	26400.0	11.70	3.30	5	5.25	.46		52.84	5.96		4.56	2.02		18.68	1.43
5.50	45.00	2.30	16.60	25100.0	11.30	2.90	1	5.49	.11		41.20	3.30		5.40			17.60	
4.30	45.00	2.50	20.10	17400.0	12.80	7.90	2	4.72	.18		38.00	2.00		5.60	.60		17.30	1.90
5.20	55.00	1.20	24.00	18800.0	12.80	5.20	5	5.05	.16		52.60	2.86		3.38	.54		16.00	.22
5.30	45.00						4	5.18	.05		48.00	2.44						
5.50	45.00						8	5.25	.50		42.90	3.43		2.60	1.10		17.30	2.35
4.30	45.00	2.50	20.10	17400.0	12.80	7.90	1	4.32			44.40			6.20			16.50	
5.50	47.90	1.30	18.50	26400.0	11.70	3.30	11	5.35	.33		51.05	3.33		2.27	.42		18.31	1.93
4.50	45.00	2.30	20.70	13300.0	13.30	9.20	1	5.16			42.20			3.10			15.00	

APPENDIX E

DFC PAVEMENT PARAMETERS

Table E-1 Difference From Target For Percent Retained 4.75 mm Sieve

	Total		Traprock		Steel Slag	
	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing
45% DFC						
Mean	0.9	0.8	-1.1	0.1	1.7	1.2
Std Dev	3.4	3.8	3.0	3.3	3.1	3.9
55% DFC						
Mean	-1.8	-2.8	0.0	-2.1	-2.7	-3.1
Std Dev	2.2	3.6	1.4	5.4	2.0	2.7

Table E-2 Difference From Target For A.C. Content by Aggregate Type

	Total		Traprock		Steel Slag	
	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing
45% DFC						
Mean	0.00	0.05	0.24	0.22	-0.12	-0.05
Std Dev	0.26	0.29	0.19	0.20	0.22	0.29
55% DFC						
Mean	-0.05	0.07	-0.01	0.13	-0.07	0.03
Std Dev	0.19	0.20	0.12	0.11	0.22	0.24

Table E-1 Difference From Target For Percent Retained 4.75 mm Sieve

	Total		Traprock		Steel Slag	
	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing
45% DFC						
Mean	0.9	0.8	-1.1	0.1	1.7	1.2
Std Dev	3.4	3.8	3.0	3.3	3.1	3.9
55% DFC						
Mean	-1.8	-2.8	0.0	-2.1	-2.7	-3.1
Std Dev	2.2	3.6	1.4	5.4	2.0	2.7

Table E-2 Difference From Target For A.C. Content by Aggregate Type

	Total		Traprock		Steel Slag	
	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing	Plant Check	Acceptance Testing
45% DFC						
Mean	0.00	0.05	0.24	0.22	-0.12	-0.05
Std Dev	0.26	0.29	0.19	0.20	0.22	0.29
55% DFC						
Mean	-0.05	0.07	-0.01	0.13	-0.07	0.03
Std Dev	0.19	0.20	0.12	0.11	0.22	0.24

Figure E-1 : Difference from Target for Percent Retained 4.75 mm Sieve

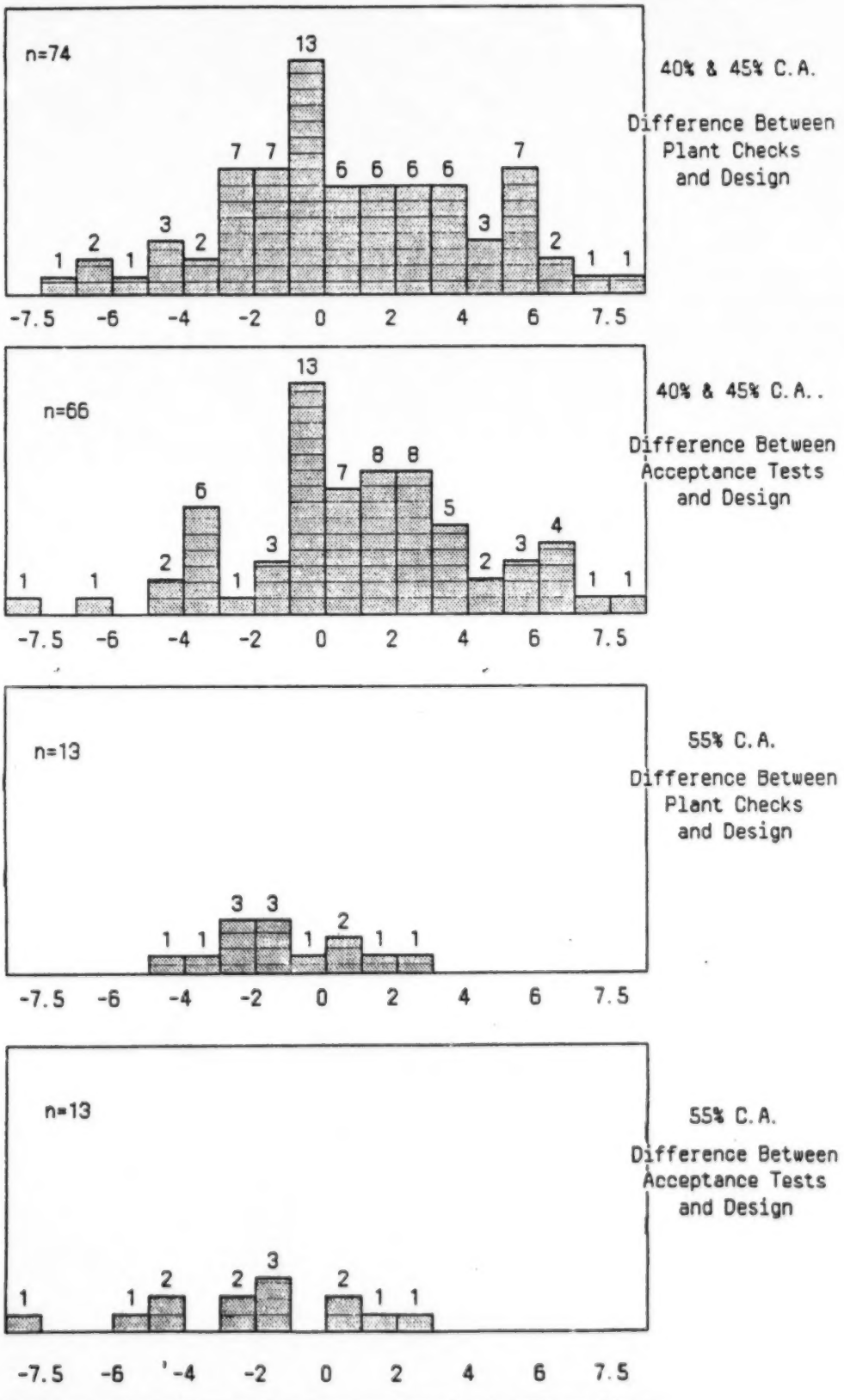

n=74
40% & 45% C.A.
Difference Between Plant Checks and Design
n=66
40% & 45% C.A..
Difference Between Acceptance Tests and Design
n=13
55% C.A.
Difference Between Plant Checks and Design
n=13
55% C.A.
Difference Between Acceptance Tests and Design
-7.5 -6 -4 -2 0 2 4 6 7.5
Number of Occurrences
Difference from Target for Percent Retained 4.75 mm Sieve

Figure E-2 : Difference from Target for Percent Retained 4.75 mm Sieve by Aggregate Type

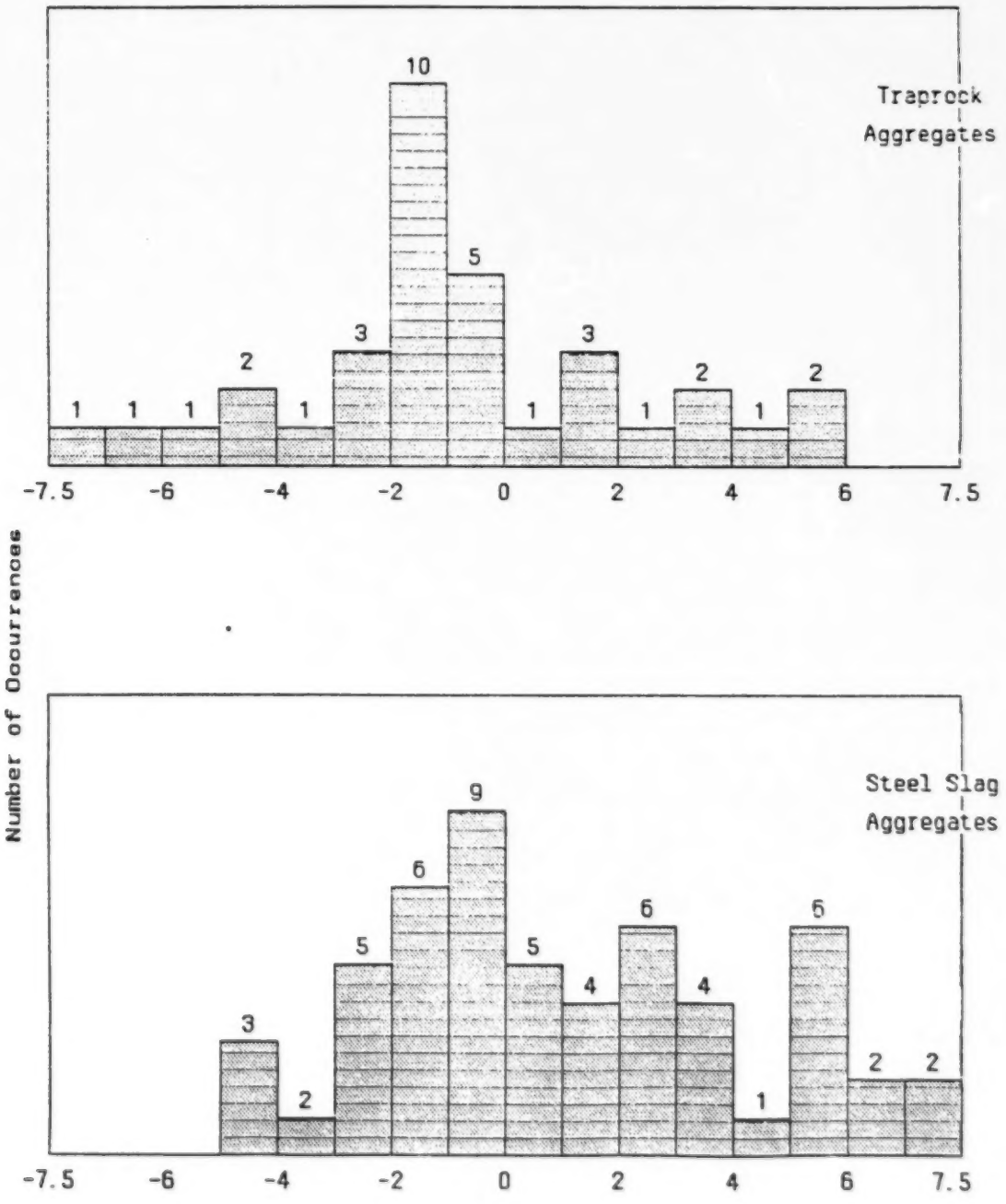
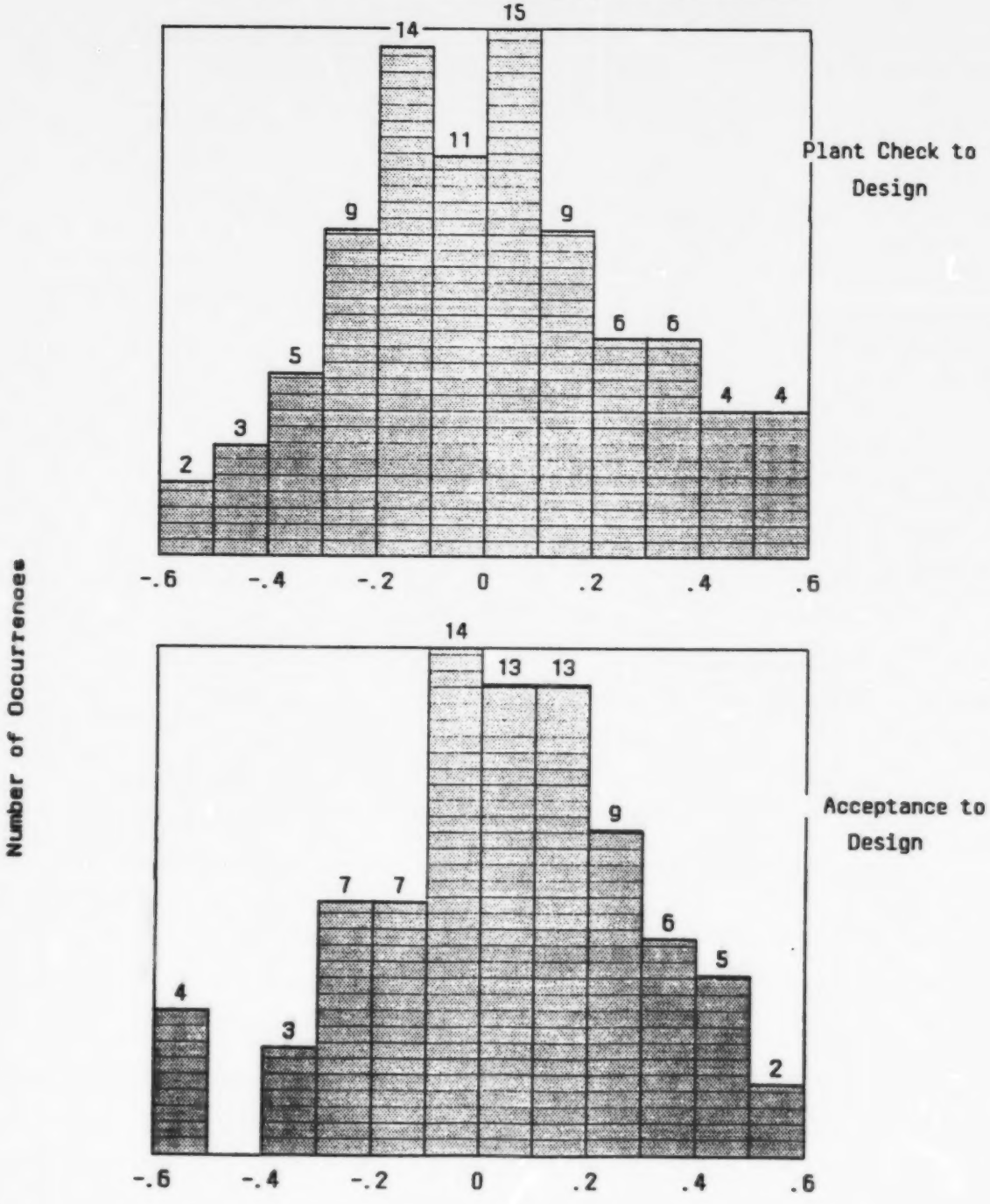

Traprock Aggregates
Steel Slag Aggregates
Number of Occurrences
1 1 1 2 1 3 10 5 1 3 1 2 1 2
3 2 5 6 9 5 4 6 4 1 6 2 2
-7.5 -6 -4 -2 0 2 4 6 7.5
Difference from Target for Percent Retained 4.75 mm Sieve (Mobile Lab)

Figure E-3 : Difference from Target for A.C. Content



Figire E-4 : Difference from Target for A.C. Content By Aggregate Type

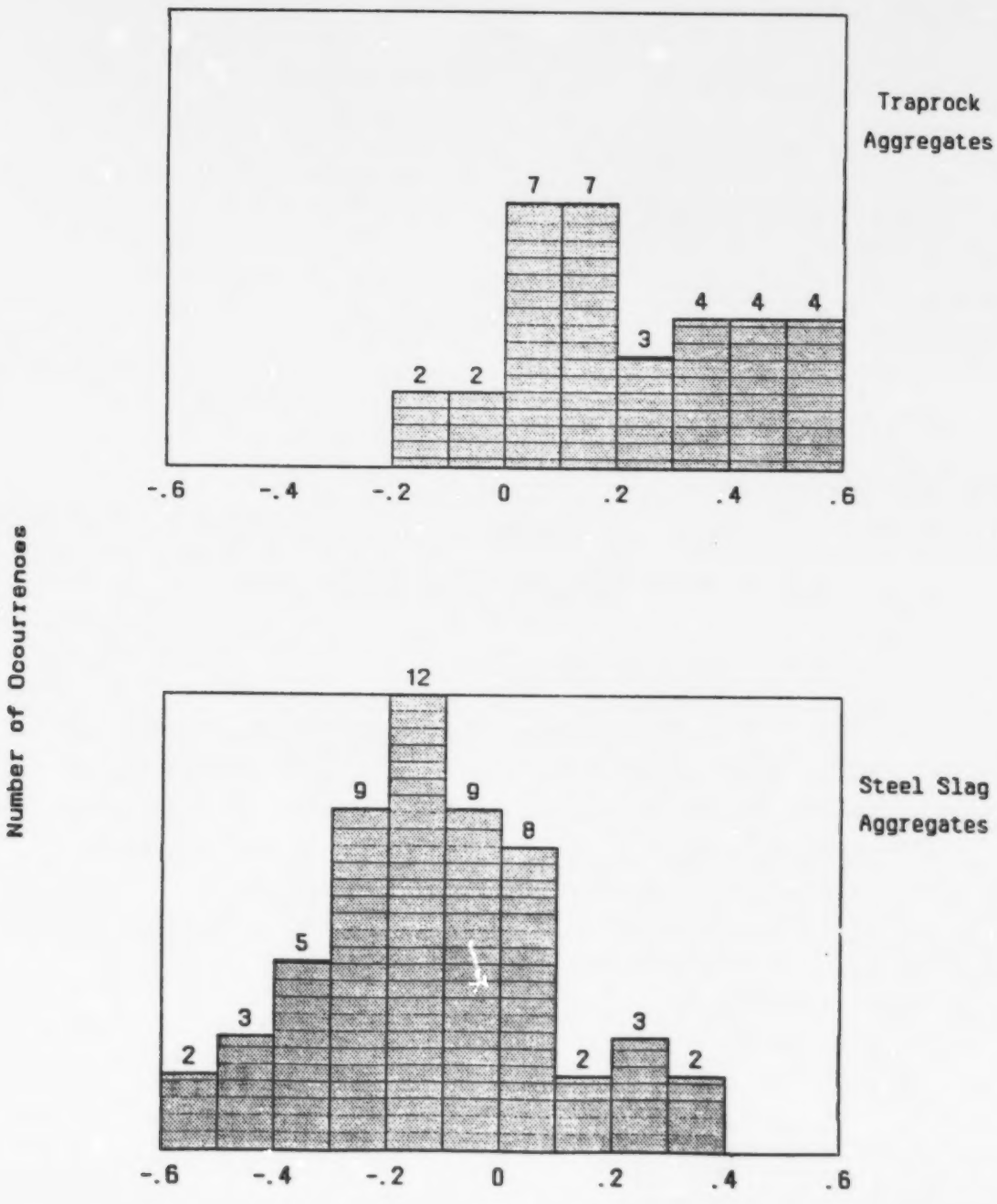

Traprock
Aggregates
2 2 7 7 3 4 4 4
-.6 -.4 -.2 0 .2 .4 .6
Steel Slag
Aggregates
2 3 5 9 12 9 8 2 3 2
-.6 -.4 -.2 0 .2 .4 .6
Number of Occurrences
Difference from Target (% A.C.)

Figure E-5 : As Constructed vs Design Stability

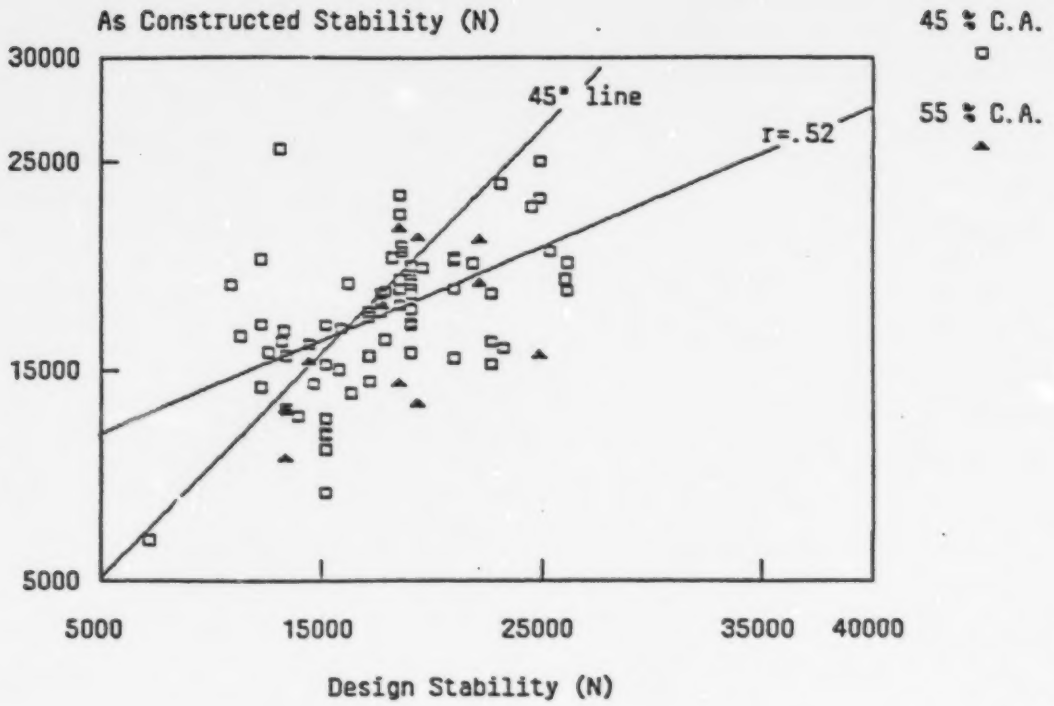
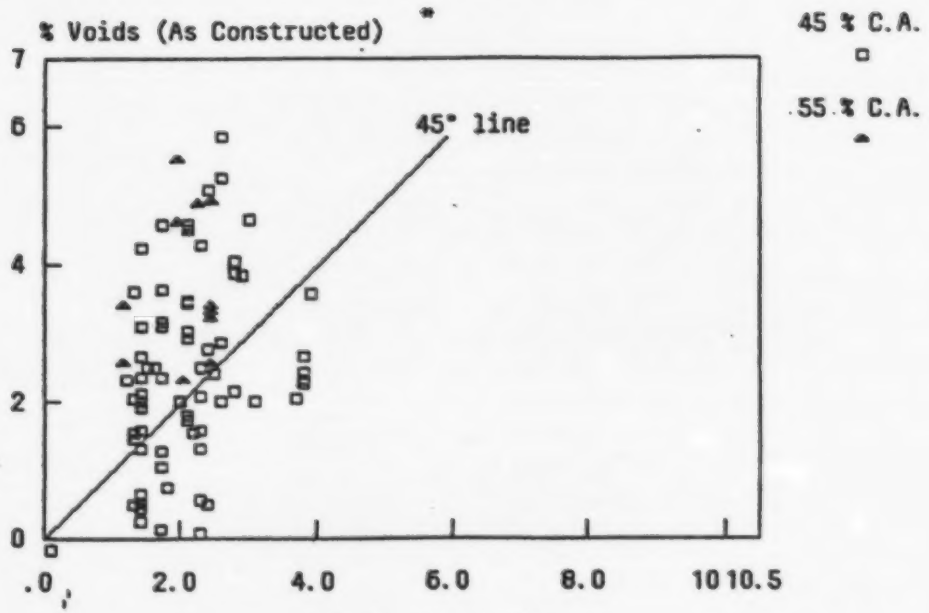


Figure E-6 : As Constructed vs Design Voids



* As Constructed represents compacted Marshall from plate samples

Figure E-7: As Constructed vs Design % VMA

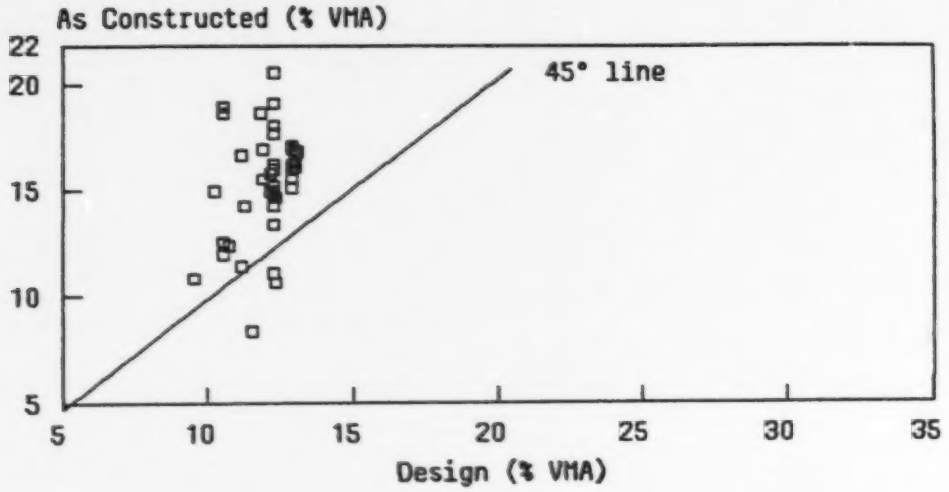
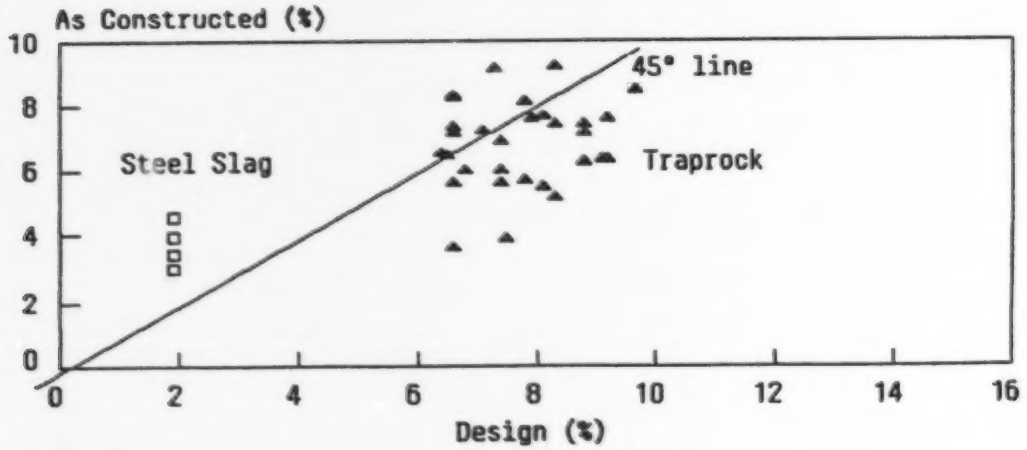


Figure E-8 : As Constructed vs Design for % Passing 75µm



APPENDIX F

MAINTENANCE SURVEY

Table F-1: Patrol Supervisor Responses to Performance Survey

District	1			2			4							6				7		8		9		
Patrol	99	20	-	17	9	18	-	9	8	16	7A	7B	15	14	-	2	7	5	41	-	14	4	-	14	-	2	1	TOTALS
7A & 7B required for two distinct pavements																												
Winter Maintenance																												
Application of salt only: -in windrows	-	-		Y	-	Y		Y	-	-	-	-	-	-		-	-	-	Y		-	-		-		Y	Y	6Y
-with spinners	Y	Y1		-	-	-		-	-	-	-	-	-	Y		Y1	-	-	-		-	-		-		-	-	4Y
Application of 15% Salt in Sand : -in windrows	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	-		-	-		-		-	-	
-with spinners	-	-		-	Y	-		-	Y	Y	Y	Y	Y	-		-	Y	Y	-		Y	-		-		-	-	9Y
Use of salt only for storms: -in windrows	-	-		-	Y	-		-	Y	-	Y	-	Y	-		-	Y	Y	-		Y	-		-		-	-	7Y
-with spinners	-	-		-	-	-		-	-	Y	Y	Y	-	-		-	-	-	-		-	-		-		-	-	4Y
Use of 30% to 50% for Storms : -in windrows	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	-		Y	-		-		-	-	1Y
-with spinners	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	-		Y	-		-		-	-	2Y
Use of 5% Salt in Sand (spinners)	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	-		-	-		-		-	-	1Y
Use of sand only	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	Y		-	-		-		-	-	
Double Applications generally required	-	-		-	-	-		Y	-	-	-	-	-	-		-	-	Y	Y		-	-		-		-	-	3Y
Problems First Winter	-	-		-	-	-		Y	-	-	-	-	-	-		-	-	Y	-		-	-		-		Y	-	4Y
Wears out Snowplow Blades (Carbide Blades)	-	-		-	-	-		-	-	-	-	-	-	-		-	-	Y	-		Y	-		-		-	-	1Y
Permeability																												
Problems with Icing/Permeability	N	N		-	N	N		-	N	N	-	N	N	N		N	N	-	-		-	-		-		N	N	12N
Perceived as Permeable by Motorists	N	N		Y	Y	-		Y	Y	Y	Y	N	Y	Y		N	N	Y	N		Y	-		Y		N	N	15Y-6N
Water gets Trapped at Curb/Gutter or Paved Shoulder	N	N		-	-	-		Y	Y	Y	Y	N	Y	-		N	-	Y	N		Y	Y		Y		-	-	7Y-5N
Tends to Hold Dampness/Snow Longer	N	N		-	Y	-		Y	-	-	Y	N	Y	N		-	N	Y	N		Y	Y		Y		N	-	5Y-7N
Drainage at Open Shoulder	-	-		Y	N	Y		-	-	-	N	-	-	-		-	-	-	-		-	Y		-		-	-	3Y-2N
Freezing with Open Shoulders	-	-		N	Y	N		-	-	-	Y	-	-	-		-	-	-	-		-	N		-		-	-	2Y-2N
Less Spray than Dense Graded Mix (HL1)	-	-		-	-	-		-	-	-	-	-	-	-		-	-	-	-		-	-		-		-	-	
More Spray than OFC Pavements	-	-		-	-	-		Y	-	-	-	-	-	-		Y	-	Y	N		-	-		-		-	-	2Y-1N
Tends to Ice Faster than Adjacent Dense Pavements	-	-		N	-	-		-	-	Y	-	-	-	N		-	-	Y	N		Y	-		Y		N	-	0Y-3N
Voids Appear to Plug After 1 or 2 Winters	-	-		-	-	-		Y	-	-	-	Y	-	-		-	-	-	-		-	-		-		Y	-	2Y
No Change in Permeability over the years	Y	Y		-	-	-		N	-	-	-	Y	-	Y		Y	-	-	-		-	N		-		-	Y	7Y-2N
Other Comments																												
Ravelling Occurring -at potholes	-	Y		Y	Y	Y		-	-	-	Y	Y	Y	-		-	N	-	N		-	N		Y		-	-	8Y-3N
-at cracks/joints	-	-		-	-	-		-	-	-	Y	Y	Y	-		-	N	-	N		-	N		-		-	-	4Y-3N
Cracking	Y	Y		N	-	-		-	-	Y	Y	Y	Y	-		Y	N	-	N		Y	-		-		-	-	8Y-1N
Leaching	N	N		N	-	N		N	N	N	-	N	N	N		N	-	-	-		-	-		-		-	-	1NN
Wheel Rutting	-	-		-	-	-		-	-	-	-	-	Y	-		-	-	-	-		-	-		-		-	-	1Y
Footnotes																												
Y1 : Slow spinners																												
Y : Situation occurs																												
N : Situation Does Not Occur																												
- : No Comment (Not reviewed)																												
Patrol 99 : City of Windsor																												

TABLE F-2: Contracts Under Patrols

Cont./Patrol	99	20	-	17	9	10	-	9	8	16	7A	7B	15	14	-	2	7	6	41	-	14	4	-	14	-
	80-33 80-43 80-04	78-55		80-38	W.R.	P.R.		79-80 79-113 81-72 82-34	82-55 83-11 80-30 83-41	81-56	78-83 79-102	82-59	81-66 80-01	79-143		79-25 81-67 83-69 83-71 80-71	79-130 80-22 81-61	79-74 83-20 82-53	82-41		80-55 82-61 82-03	79-102		78-12	

WR City of Windsor
PR Plark's Rd

Table F-3: Patrol Supervisor Responses for Impermeable Pavements

District	1			6			9		
Headings/Patrols	99	20	-	2	7	-	2	1	TOTALS
District :	1	1		6	6		9	9	
Winter Maintenance									
Application of Clear Salt Always: -in windrows	-	-		-	-		Y	Y	2Y
-with spinners	Y	Y1		Y1	-		-	-	2Y
Application of 15% Salt in Sand : -with spinners	-	-		-	Y		-	-	1Y
Use of Clear Salt for Storms : -in windrows	-	-		-	Y		-	-	1Y
Problems First Winter	-	-		-	-		Y	-	1Y
Permeability									
Problems with Icing/Permeability	N	N		N	N		N	N	6N
Perceived as Permeable by Patrolman	N	N		N	N		N	N	6N
Water gets Trapped at Curb/Gutter or Paved Shoulder	N	N		N	-		-	-	3N
Tends to Hold Dampness/Snow Longer	N	N		-	N		N	-	4N
More Spray than DFC Pavements	-	-		Y	-		-	-	1Y
Tends to Ice Faster than Adjacent Dense Pavements	-	-		-	-		N	-	1N
Voids Appear to Plug After 1 or 2 Winters	-	-		-	-		Y	-	1Y
No Change in Permeability over the years	Y	Y		Y	-		-	Y	4Y
Other Comments									
Ravelling Occurring -as pervales	-	Y		-	N		-	-	1Y-1N
-at cracks/cold joints	-	-		-	N		-	-	1N
Cracking	Y	Y		Y	-		-	-	3Y
Leaching	N	N		N	N		-	-	4N

Table F-4: Patrol Supervisor Responses for Permeable Pavements

District	2			4						6			7		8		
Headings/Patrols	17	9	10	-	8	16	7A	7B	15	14	-	6	41	-	14	4	-	14	TOTALS
Winter Maintenance																			
Application of Clear Salt Always: -in windrows	Y	-	Y		Y	-	-	-	-	-		-	Y		-	-		-	4Y
-with spinners	-	-	-		-	-	-	-	-	Y		-	-		-	-		-	1Y
Application of 15% Salt in Sand : -with spinners	-	Y	-		-	Y	Y	Y	Y	-		Y	-		-	-		-	5Y
Use of Clear Salt for Storms : -in windrows	-	Y	-		-	Y	-	-	Y	-		Y	-		-	-		Y	5Y
-with spinners	-	-	-		-	Y	Y	Y	-	-		-	-		-	-		-	4Y
Use of 20% to 50% for Storms : -in windrows	-	-	-		-	-	-	-	-	-		-	-		-	-		-	1Y
-with spinners	-	-	-		-	-	-	-	-	-		-	-		-	-		-	2Y
Use of 5% Salt in Sand (spinners)	-	-	-		-	-	-	-	-	-		-	-		-	-		-	1Y
Use of Clear Sand	-	-	-		-	-	-	-	-	-		-	Y		-	-		-	1Y
Double Applications generally required	-	-	-		Y	-	-	-	-	-		Y	Y		-	-		-	3Y
Problems First Winter	-	-	-		Y	-	-	-	-	-		Y	-		-	-		-	2Y
Meets our Snowplow Blades (Carbide Blades)	-	-	-		-	-	-	-	-	-		Y	-		-	-		-	1Y
Permeability																			
Problems with Icing/Permeability	-	N	N		-	N	N	-	N	N	N		-		-	-		-	7N
Perceived as Permeable by Patrolman	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y		Y	N	Y	Y		Y	15Y
Water gets Trapped at Curb/Gutter/Paved Shoulder	-	-	-		Y	-	Y	Y	N	Y	N		Y	N	Y	Y		Y	7Y-3N
Tends to Hold Dampness/Snow Longer	-	Y	-		Y	-	Y	Y	N	Y	N		Y	N	Y	Y		Y	9Y-3N
Drainage at Open Shoulders	Y	N	Y		-	-	-	N	-	-	-		-	-	Y	Y		Y	3Y-3N
Freezing with Open Shoulders	N	Y	N		-	-	-	Y	-	-	-		-	-	Y	Y		Y	2Y-3N
Less Spray than Dense Graded Mix (ML1)	-	-	-		-	-	-	-	-	-	-		-	Y	Y	Y		Y	1Y
More Spray than DFC Pavements	-	-	-		Y	-	-	-	-	-	-		Y	N	Y	Y		Y	2Y-1N
Tends to Ice Faster than Adjacent Dense Pavements	N	Y	-		-	-	Y	-	-	N	-		Y	-	Y	Y		Y	4Y-2N
Voids Appear to Plug After 1 or 2 Winters	-	-	-		Y	-	-	-	-	-	-		-	-	Y	Y		Y	1Y
No Change in Permeability over the years	-	-	-		N	-	-	-	Y	-	Y		-	-	N	Y		Y	2Y-2N
Other Comments																			
Ravelling Occurring -as pervales	Y	Y	Y		-	-	-	Y	Y	Y	-		-	N	-	N		Y	6Y-3N
-at cracks/cold joints	-	-	Y		-	-	-	Y	Y	Y	-		-	N	-	N		-	4Y-3N
Cracking	N	-	-		-	-	Y	Y	Y	Y	-		-	-	-	-		-	5Y-1N
Leaching	N	-	N		N	N	N	N	N	N	N		-	-	-	-		-	1+8N
Wheel Rutting	-	-	-		-	-	-	-	Y	-									1Y

APPENDIX G

PERMEABILITY

APPENDIX G

Permeability Evaluation Highway 401
From Oshawa to Highway 115

The most extensive data on DFC permeability comes from the Highway 401 sections in Port Hope District from east of Oshawa to Highway 115. During the winter of 1982/83, Highway 401 in this area experienced severe icing conditions several times. This section of Highway had been resurfaced/reconstructed under three contracts: Contracts 80-55, 82-81 and 82-03.

The DFC on Contract 80-55 was placed in September and October of 1981. The total contract tonnage was not placed and work was completed under Contract 82-81. For Contract 82-81 the work was completed in July 1982. For Contract 82-03 the DFC was placed in October and early November 1982 with the exception of a small full-width section on Highway 401 in the vicinity of Liberty Street (Sta. 432+00) which was placed in May 1983.

The general design on all three contracts provided for three lanes of DFC with HL 4 paved shoulders. In the summer of 1983, a coring program of the DFC was completed in this stretch for the purpose of testing permeability (FHWA method), percent in-place pavement voids, gradation of extracted aggregate, percent compaction, and percentage asphalt cement. The test results are given in Table G-1.

In the coring program, random cores (random by offset and station) were taken on all three contracts. For Contract 82-03, the sections where most of the cores were taken on Highway 401 were paved October 13 to 18, 1982 with afternoon ambient temperatures (2 o'clock) ranging from 12° C to 17° C and morning ambient temperatures (8 o'clock) ranging from 5° C to 13° C. The cores at the Stations 455+00 and 454+83 represent material placed on the spring of 1983. The sections on Highway 115 were paved in late October and early November 1982 and these areas exhibited some ravelling immediately after construction. None of the cores for this evaluation came from this area.

A comparison was made of in-place pavement voids (determined from cores), air voids from recompacted Marshall briquettes in the laboratory plant check and actual design air voids for the three contracts and four job mixes (Table G-2). In all cases the in-place pavement voids were substantially higher than the design and recompacted Marshall voids. The air voids from recompacted Marshall plant checks for the stonier mixes are significantly higher than the design voids.

TABLE G-2: (AIR VOIDS) HIGHWAY 401 (OSHAWA TO HIGHWAY 115)

			Air Voids		
Contract	Design % C.A.	Actual % A.C. [1]	Design %	Mobile % [2]	In-Place [3]
80-55	45	40.8 (44.6)[4]	1.3	.89	10.5
82-81	45	42.4	1.3	2.68	10.9
	55	53.2	2.0	4.56	13.3
82-03	55	55.9	2.0	4.57	16.7

1. Mean mobile laboratory plant check.
2. Mean void content from laboratory plant check (Recompacted Marshall)
3. Mean in-place pavement void content from cores
4. Mean field check value.

TABLE G-1: RESULTS OF LAB TESTS : Cont 82-03, 82-81, 80-55

W/B ↓ E/B ↑

Note :

SHLDR is an HL4 pavement
W/T and C/L is DFC pavement

First Value = % Pavement Voids
Second Value = % Compaction
Third Value = % Ret 4.75mm Sieve
Fourth Value = Permeability (cm/s)

Avg. DFC Permeability :

Cont 82-03 =0.242 cm/s
Cont 82-81 =0.33 cm/s
Cont 80-55 =0.0082 cm/s

(excluding segregated sample at STN 318+32 W/T)

Cont 82-03

SHLDR	W/T	C/L	STN
7.8	21.6	19.5	573+84
94.6	83.6	85.8	
38.9	-	58.7	
	0.645	0.446	
8.1	18.3	16.1	532+39
93.6	87.0	89.3	
40.2	-	53.9	
	0.124	0.167	
7.9	17.4	18.0	520+17
94.4	87.0	87.6	
40.9	-	55.8	
	0.150	0.221	
-	14.2	12.8	477+09
-	92.4	92.2	
42.1	-	50.6	
0.0005	0.044	0.044	
11.0	16.2	17.6	474+71
93.2	89.3	91.3	
37.5	65.4	61.2	
	0.302	0.204	
-	13.8	15.0	455+00
-	91.9	91.5	
-	55.0	53.9	
-	17.6	16.1	454+83
-	86.7	89.8	
-	55.0	56.5	
	0.125	0.434	

Waverly Rd.

Cont 82-81

SHLDR	W/T	C/L	STN
7.9	12.6	11.5	383+04
96.7	91.0	91.6	
-	-	45.9	
	0.037	0.049	
7.9	10.0	8.6	333+77
96.3	94.7	94.7	
-	-	42.3	
-	0.011	0.009	
8.9	11.4	11.4	275+39
96.4	91.9	92.6	
-	-	43.4	
	0.005	0.008	
7.6	13.6	13.2	259+29
96.7	91.8	91.7	
42.6	-	52.4	
	0.051	0.020	
-	13.5	13.0	174+44
-	92.4	91.8	
47.7	-	53.5	
	0.123	0.017	

Cont 80-55

SHLDR	W/T	C/L	STN
6.2	10.4	11.6	346+48
96.6	92.5	91.5	
-	-	32.7	
	0.009	0.003	
-	13.0	7.2	318+32
-	93.2	94.1	
42.2	47.0	24.9	
	0.090	0.028	
-	8.5	10.7	256+94
-	94.5	91.5	
-	-	42.2	
	0.002	0.001	
-	10.6	12.3	233+80
-	92.8	91.2	
-	-	41.1	
	0.001	0.014	
6.0	9.3	11.6	102+68
95.9	94.6	90.5	
42.5	-	37.0	
	0.011	0.005	

Harmony Rd.

APPENDIX G

The average permeabilities (shown in Table G-3) indicate that the mixes on all of the contracts are permeable by definition (i.e. 10^{-3} cm/s for FHWA test method). The cores with lower coarse aggregate content indicate lower permeability. The permeability of Contract 82-03 (2.4×10^{-1} cm/s) is comparable to that of an OFC.

Table G-3: Permeabilities Highway 401 (Oshawa to Highway 115)

Contract	Actual % C.A.(1)	Average Permeability(2) (cm/s)
80-55	37	8.2×10^{-3} (3)
82-81	44	2.0×10^{-2}
	53	5.3×10^{-2}
82-03	57	2.4×10^{-1}

1 From cores
2 FHWA test method
3 Excluding one test at 9.0×10^{-2} because of segregation.

From the data given in Table G-1 the following graphs were made:

1) % Compaction versus % In-Place Pavement Voids (Figure G-1)

2) % In-place Pavements Voids versus Permeability (Figure G-2)

3) Percent Retained 4.75 mm versus % In-Place Pavement Voids (Figure G-3)

4) Percent Retained 4.75 mm versus % Compaction (Figure G-4)

5) Permeability versus Compaction (Figure G-5)

The test results show a good correlation for the variables studied. As expected, in Figure G-1 the percent in-place pavement voids shows excellent correlation with percent compaction ($r = 0.90$). An inverse relationship exists between these two variables i.e. as the percent compaction decreases the percent pavement voids increases.

The permeability shows a direct relationship to the in-place pavement voids (Figure G-2, $r = 0.80$). The in-place pavement voids shows a strong relationship to the coarse aggregate content (Figure G-3, $r = 0.84$). The increase in in-place pavement voids has two apparent causes. Firstly, the stonier mixes had higher recompacted Marshall void contents than the design voids by an average of 2.5% (Table G-2). Secondly, there was a trend for the stonier mixes to be harder to compact (Figure G-4, $r = 0.56$). It should be noted that none of the cores in the DFC pavement met minimum compaction requirements i.e. 95% of the laboratory density.

Finally measured permeability shows a correlation ($r = 0.73$) to percent retained 4.75 mm sieve (Figure G-5). It appears that the permeability of DFC mixes increases with an increase in coarse aggregate content.

Figure G-1: % Compaction vs In-Place Pavement Voids

(Highway 401: Oshawa to Hwy 115)

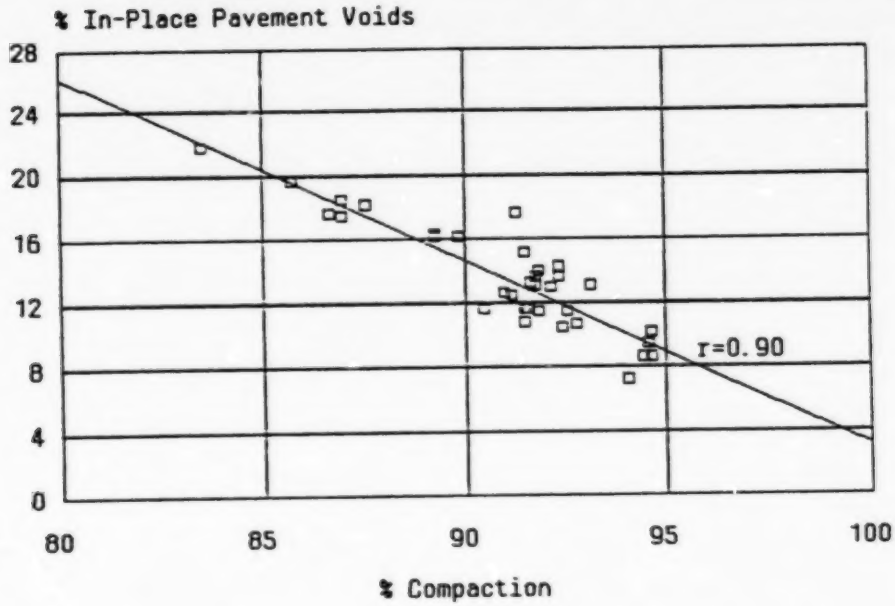


Figure G2 : % In-Place Pavement Voids vs Permeability

(Highway 401 Oshawa to Hwy 115)

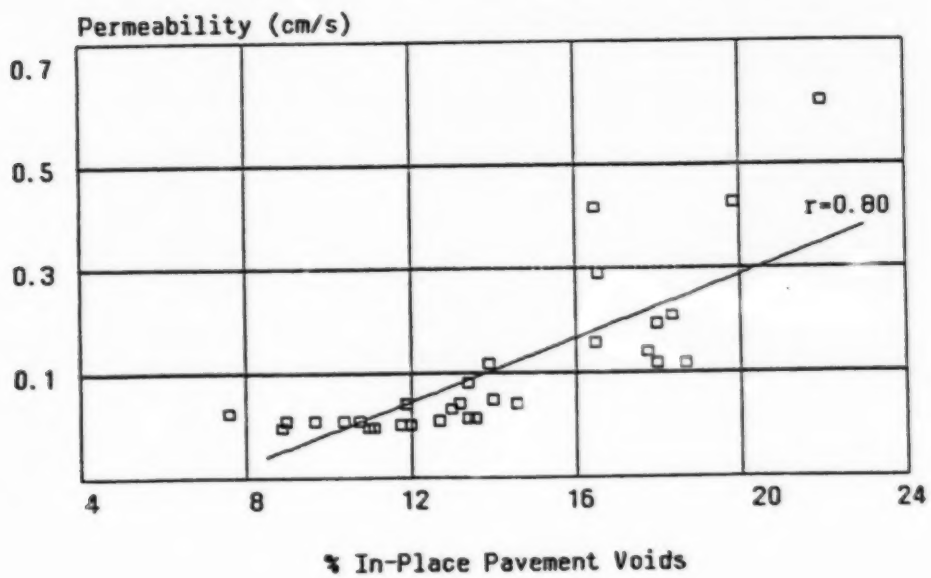


Figure G-3 : Percent Ret 4.75 mm Sieve vs % In-Place Pavement Voids
(Highway 401: Oshawa to Hwy 115)

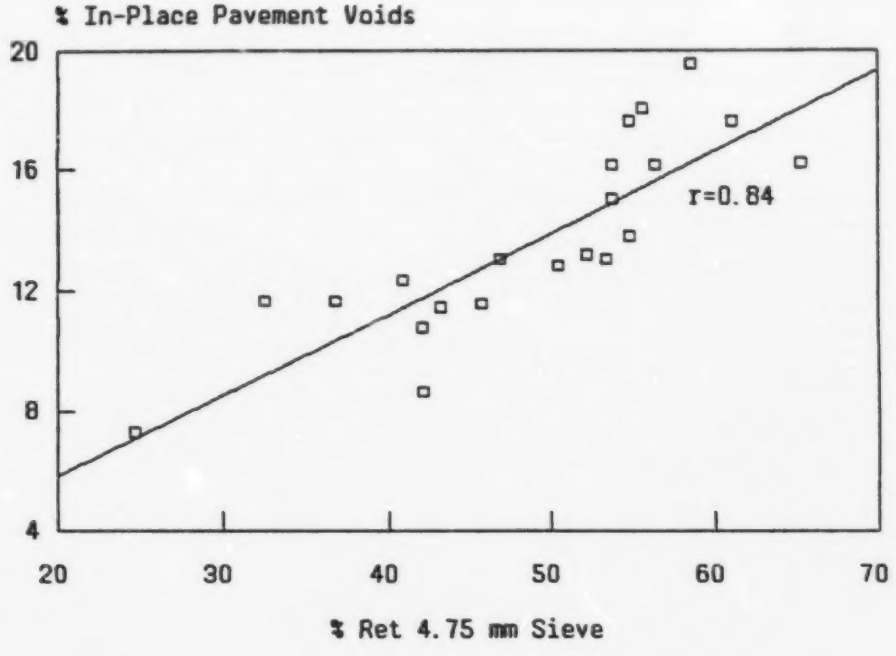
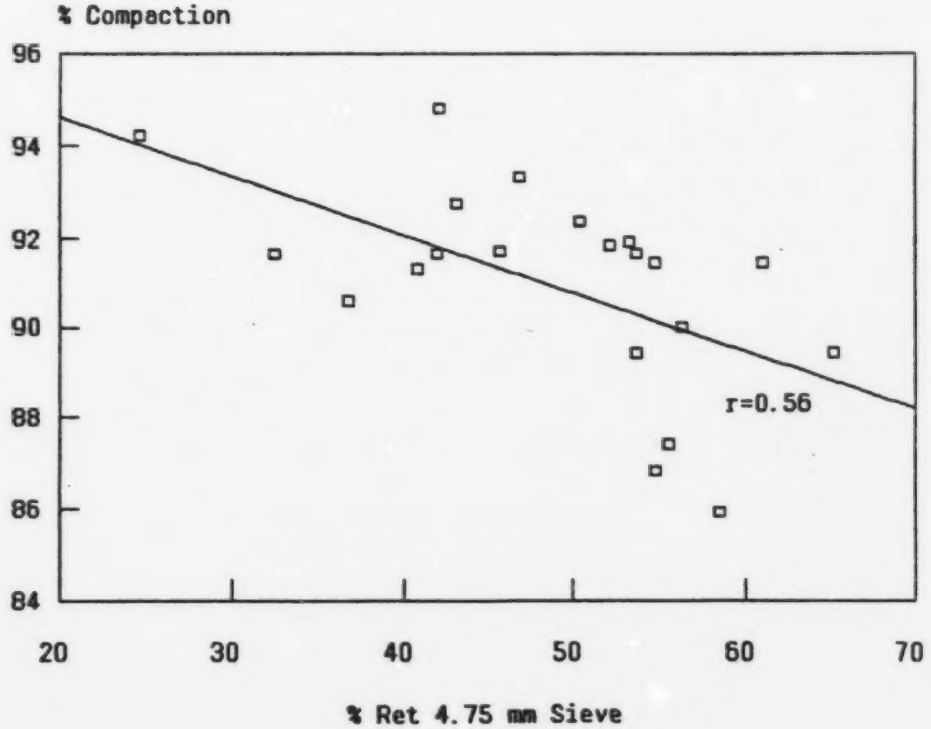


Figure G-4 : Percent Ret 4.75 mm Sieve vs% Compaction
(Highway 401: Oshawa to Hwy 115)

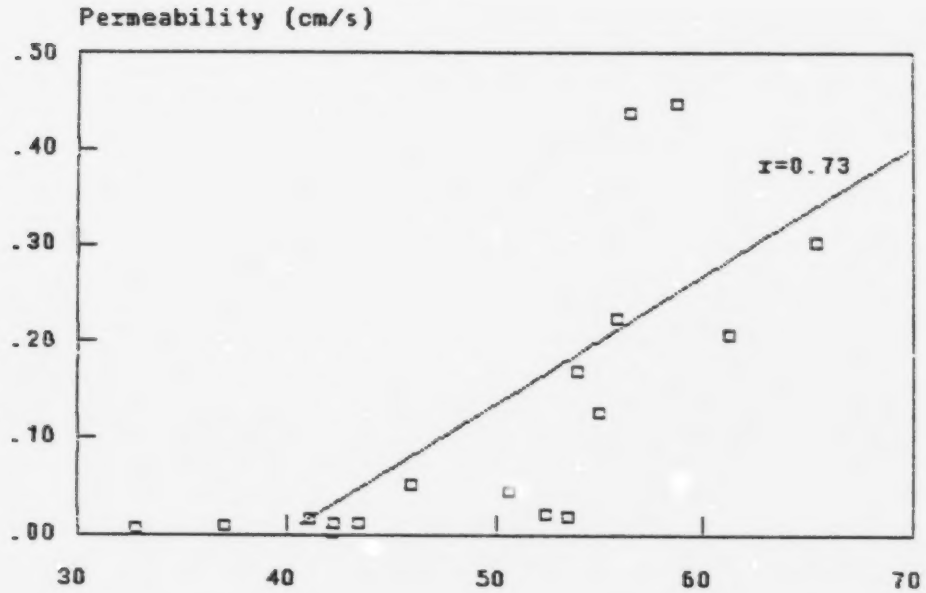


APPENDIX G

There may be other factors affecting this correlation. The earliest contract (Contract 80-55) had DFC with the lowest stone content and was in service during the 1981-82 winter. This would have contributed to some plugging of the voids thus reducing permeability. However given the low coarse aggregate content (40%) and void content (0.89), this effect would not be as significant as it would be on a higher stone/higher void mix. Also there was some concern that the high stone mix (Contract 82-03) was placed in cold weather contributing to higher voids and lower compaction. As stated previously, the sections where the cores were taken were paved in a satisfactory temperature range and cold weather paving was not a consideration.

TABLE G-5 PERMEABILITY versus PERCENT RETAINED 4.75 mm

(Highway 401 from Oshawa to Highway 115)



Percent Retained 4.75 mm sieve

(excluding seg. sample)

Given the range of parameters considered, these correlations are very good. The data came from three different contracts, four job mixes, three different mix designs over a wide range of stone contents. For all four mixes the fine aggregate was Armbro (Marmora) traprock screenings. For Contract 82-03 and Contract 82-81 (55% coarse aggregate) the coarse aggregate was 3-M Havelock traprock. For Contract 80-55 and 82-81 (45% coarse aggregate) the coarse aggregate was Armbro (Marmora) traprock.

When examining the percent compaction for the three contracts on Highway 401 it was found that the values are quite low. Since the percent compaction values are so low, the pavement voids will be (and in fact are) high, hence a high permeability. The range of compaction results demonstrated are typical of the values being achieved on many DFC installations.

APPENDIX H

MACROTEXTURE

Figure H-1 : Density of Macro-Projections vs Friction Numbers

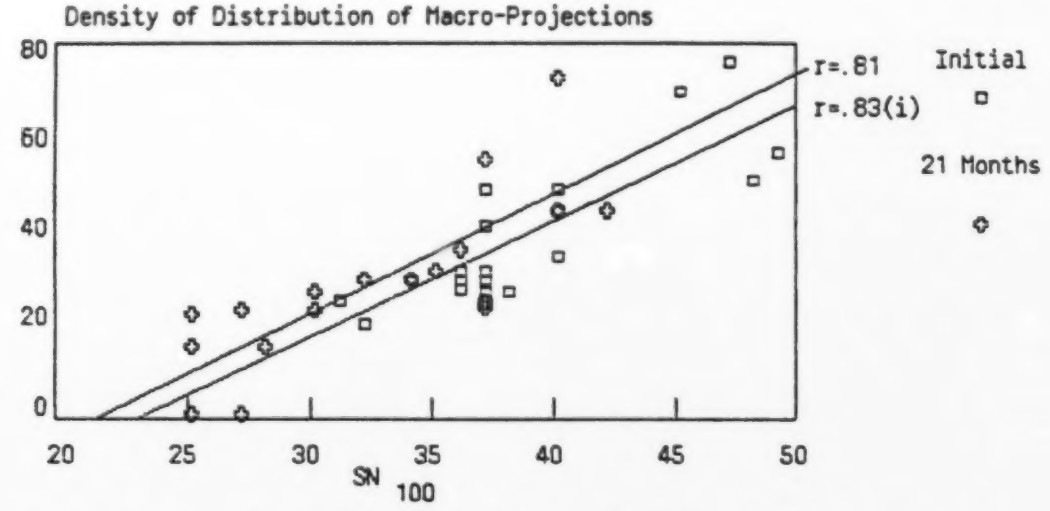
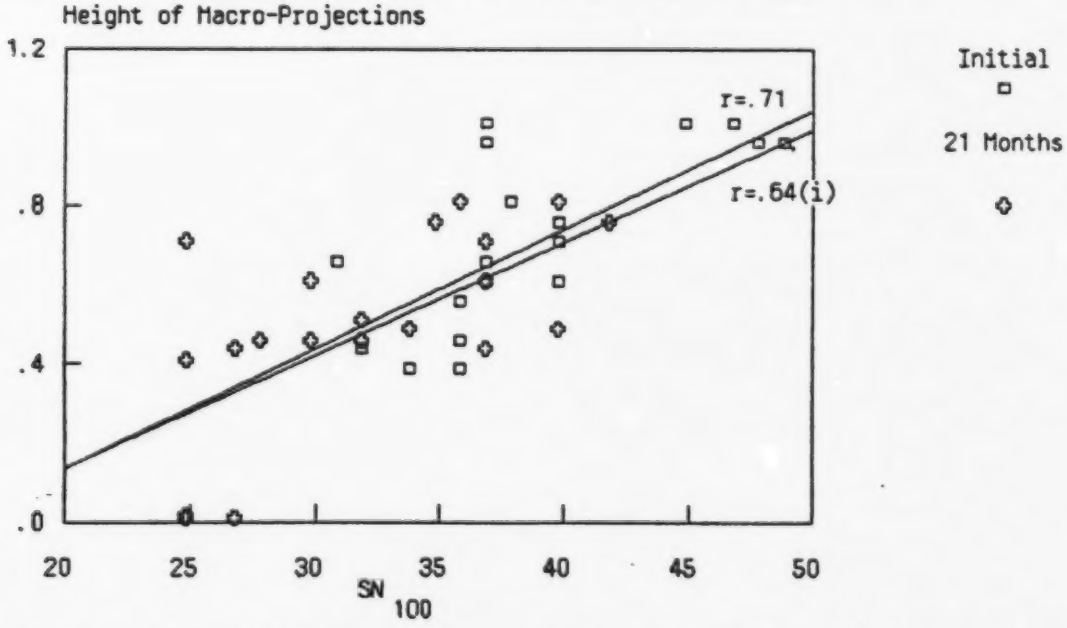


Figure H-2 : Height of Macro-Projections vs Friction Numbers



Note: Data taken from Ryell Study Hwy 401 Test Section 1-10 (D.L. and P.L.)